Robustness of the indirect Higgs width determination

Panagiotis Stylianou
Work in progress
in collaboration with Georg Weiglein

Extended Scalar Sectors From All Angles - CERN

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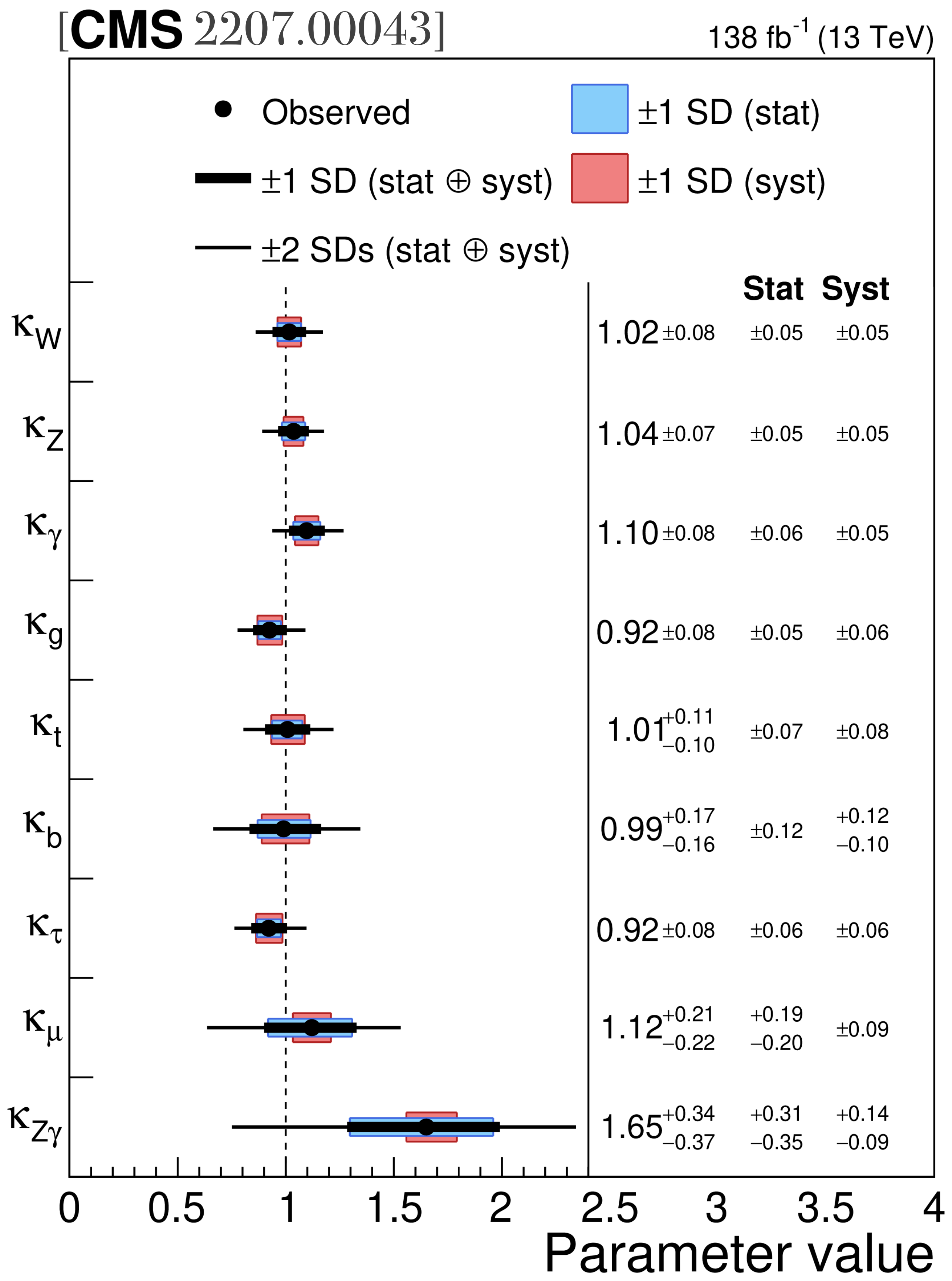
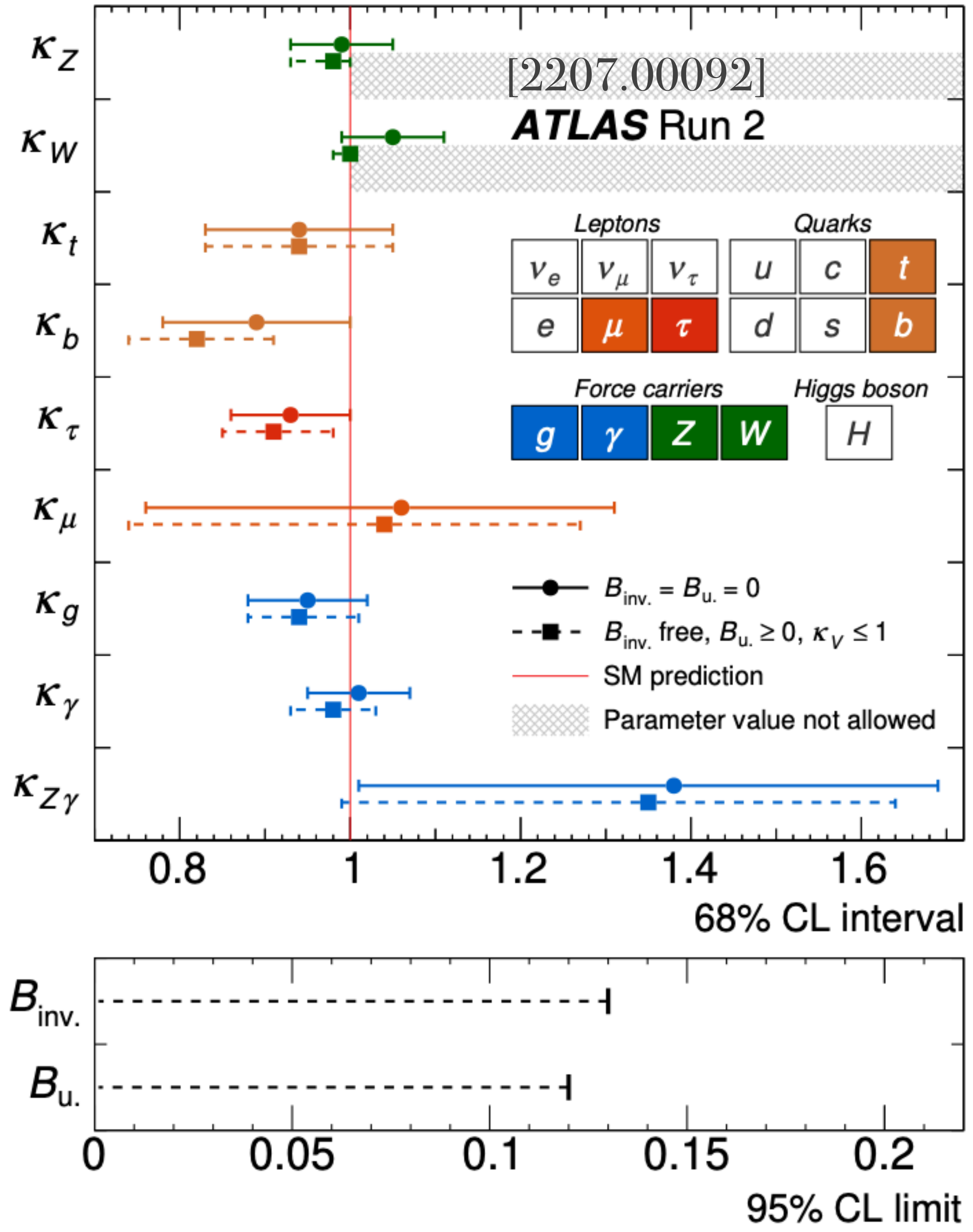
Motivation

- Measuring the couplings of the 125-GeV Higgs boson to SM particles → one of the main goals of LHC
- But the couplings are not directly accessible, experiments measure signal strengths
- When Higgs bosons are produced on-shell the signal strength depends on the total decay width of the Higgs

$$\mu_{\text{on}}(gg \to H \to ZZ) = \frac{\sigma(gg \to H)\text{BR}(H \to ZZ \to 4\ell)}{\sigma_{\text{SM}}(gg \to H)\text{BR}_{\text{SM}}(H \to ZZ \to 4\ell)} = \frac{\kappa^2_{g,\text{on}}\kappa^2_{Z,\text{on}}}{\Gamma_H/\Gamma_H^{\text{SM}}}$$





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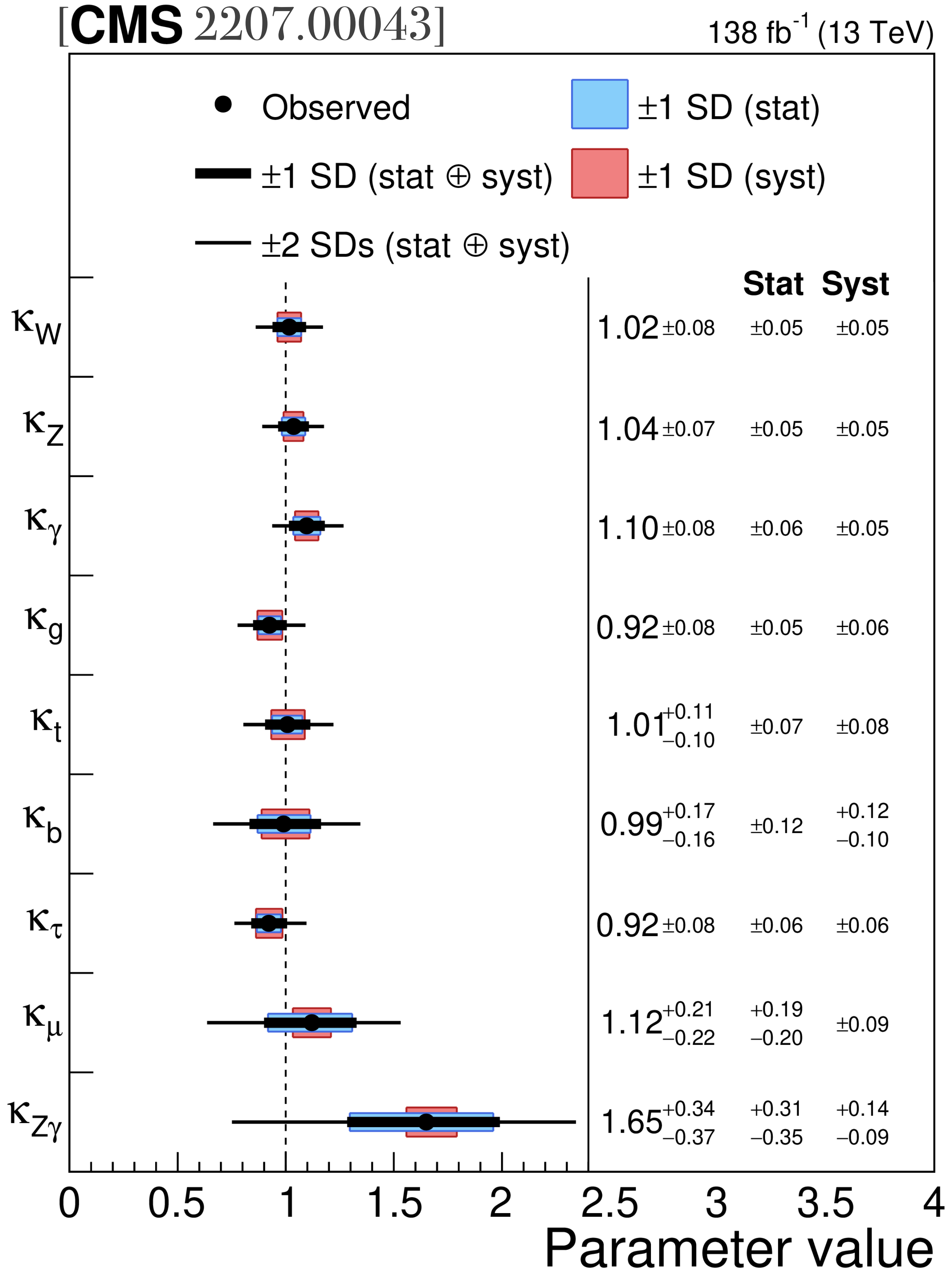
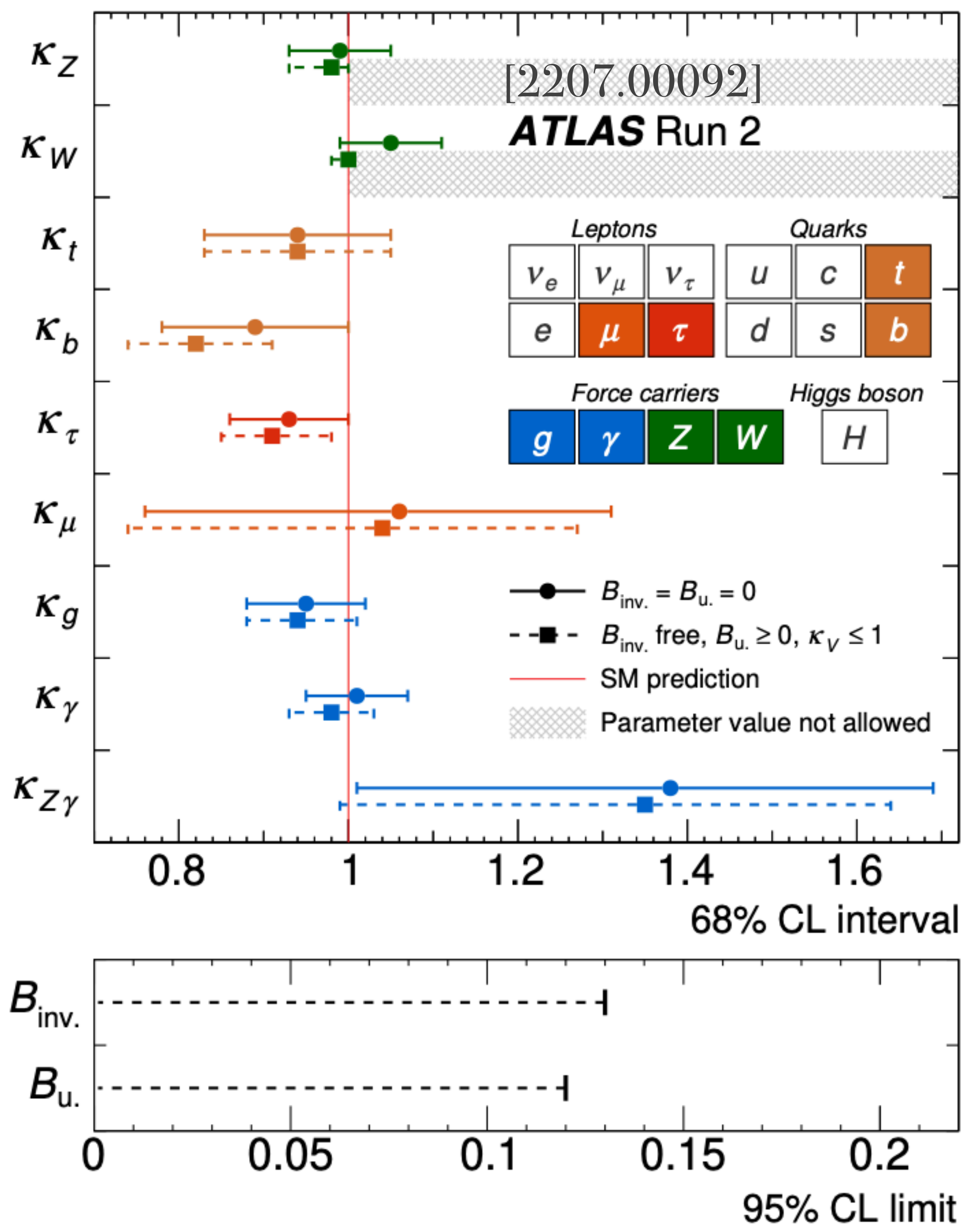
[CMS 2207.00043]



[2207.00092]



<u>SM width prediction:</u>

$$\Gamma^H = 4.1\ \text{MeV}$$

[CERN Yellow Reports V2]

<u>CMS 95%CL direct limit:</u>

$$\Gamma^H < 330\ \text{MeV}$$

[CMS 2409.13663]

<u>Direct limits</u> on the Higgs width are orders of magnitude weaker than the SM prediction

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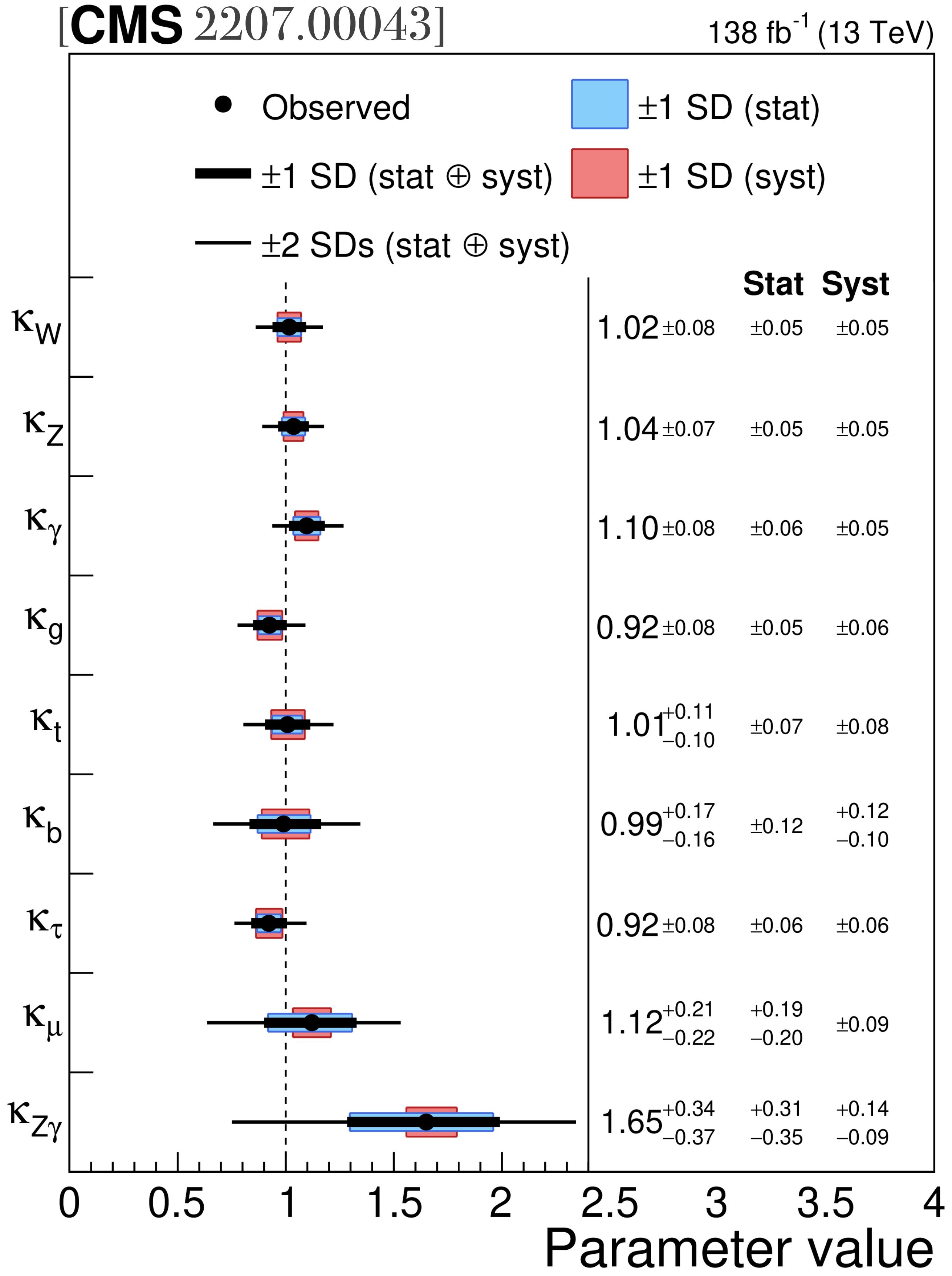

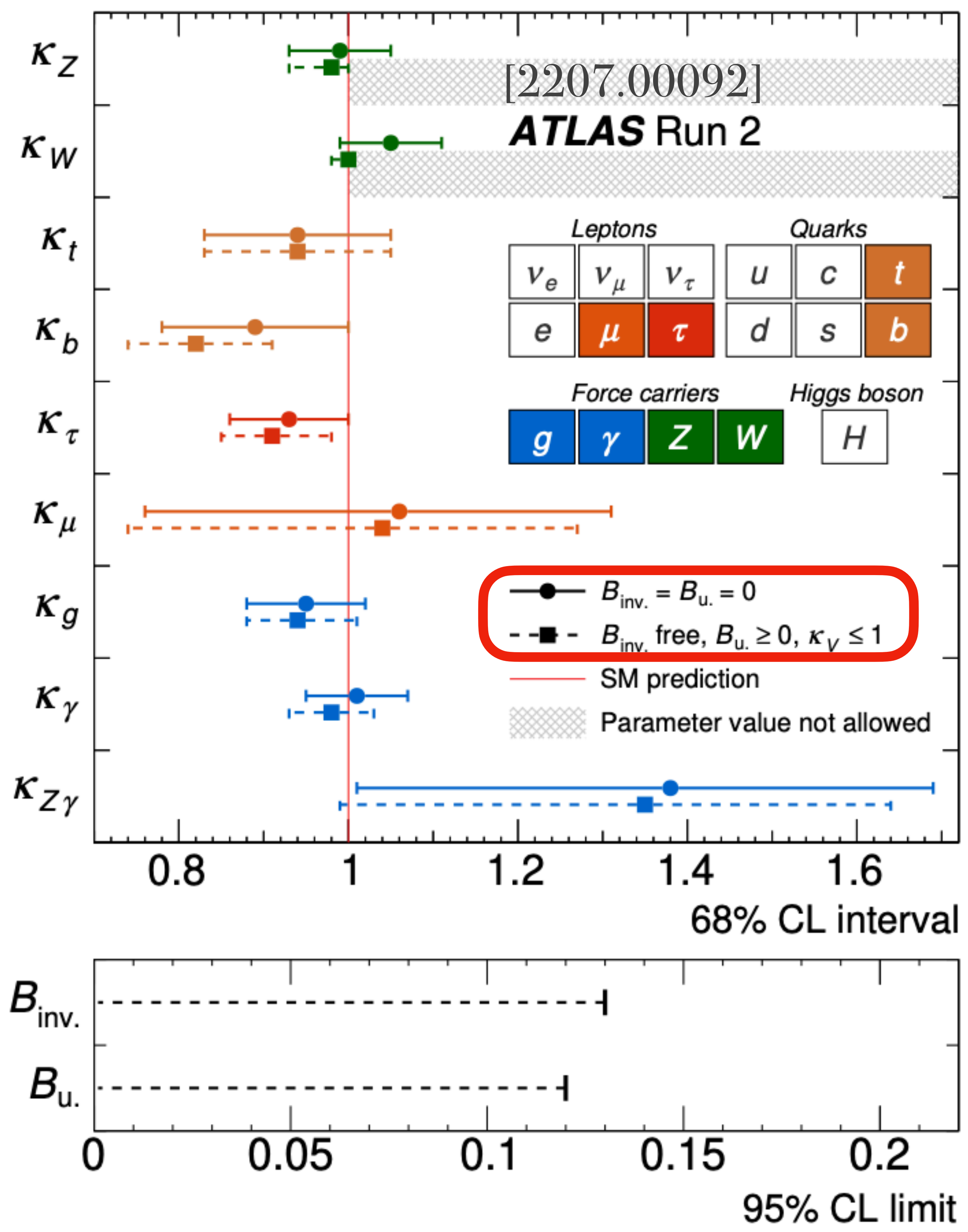

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$\Gamma^H = 4.1 \text{ MeV}$	$\Gamma^H < 330 \text{ MeV}$
[CERN Yellow Reports V2]	[CMS 2409.13663]

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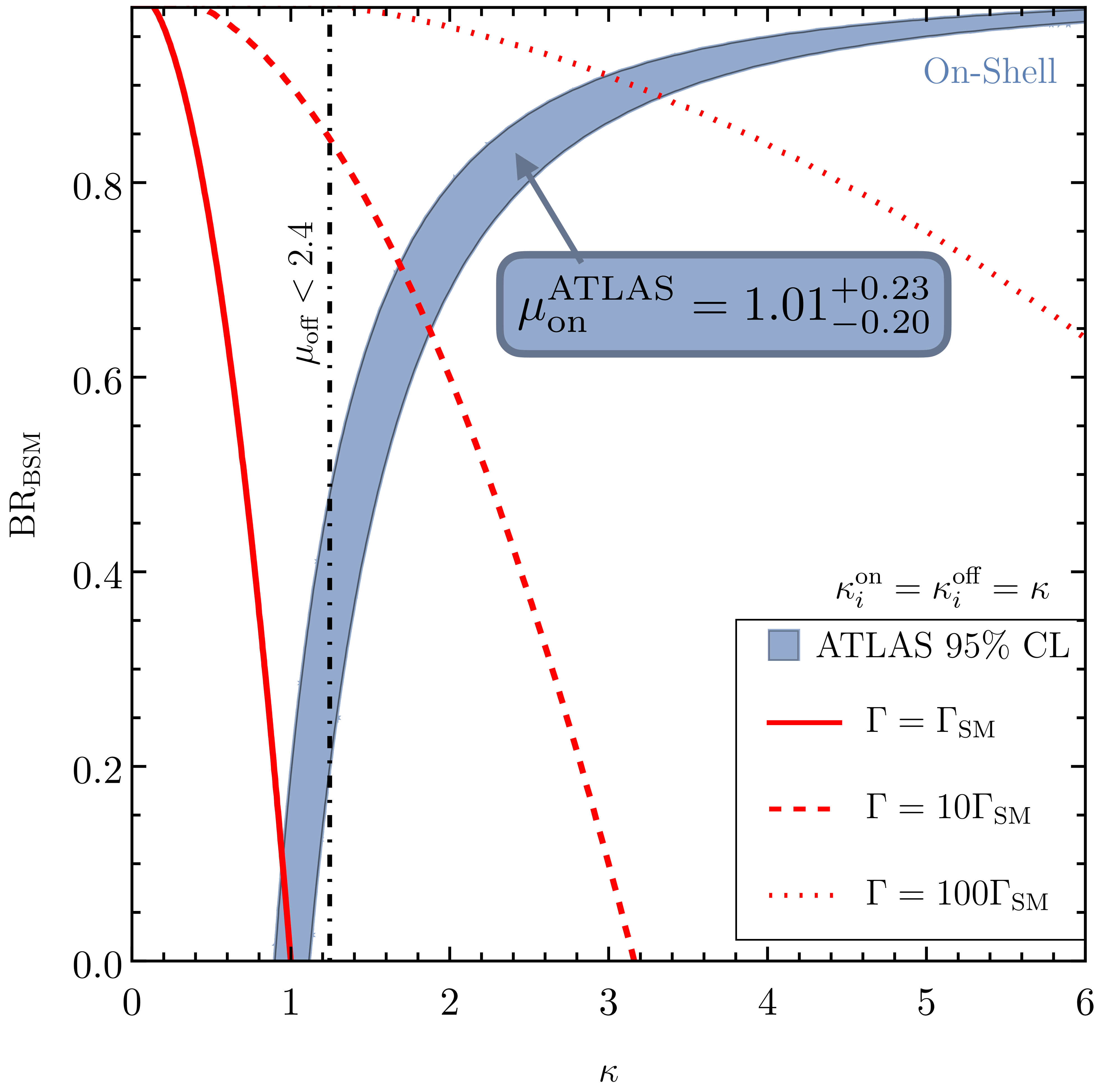
Motivation

see also: [Azatov et al `22]

- Assuming universal Higgs coupling modifiers κ and $\mu_{\text{on}} \sim 1$

$$\text{BR}_{\text{BSM}} = \frac{\kappa^2 - 1}{\kappa^2}$$

$\Longrightarrow$ **blind direction**



Indirect off-shell width measurement

- Off-shell cross section of $gg \to H \to VV$ enhanced by threshold effects [Kauer, Passarino `12]
- Can be exploited to measure the Higgs width Γ_H [Caola, Melnikov `13]
- Requires assumption $\kappa_{i,\text{off}} = \kappa_{i,\text{on}}$
- Measured by CMS & ATLAS [CMS 2202.06923] [ATLAS 2304.01532]

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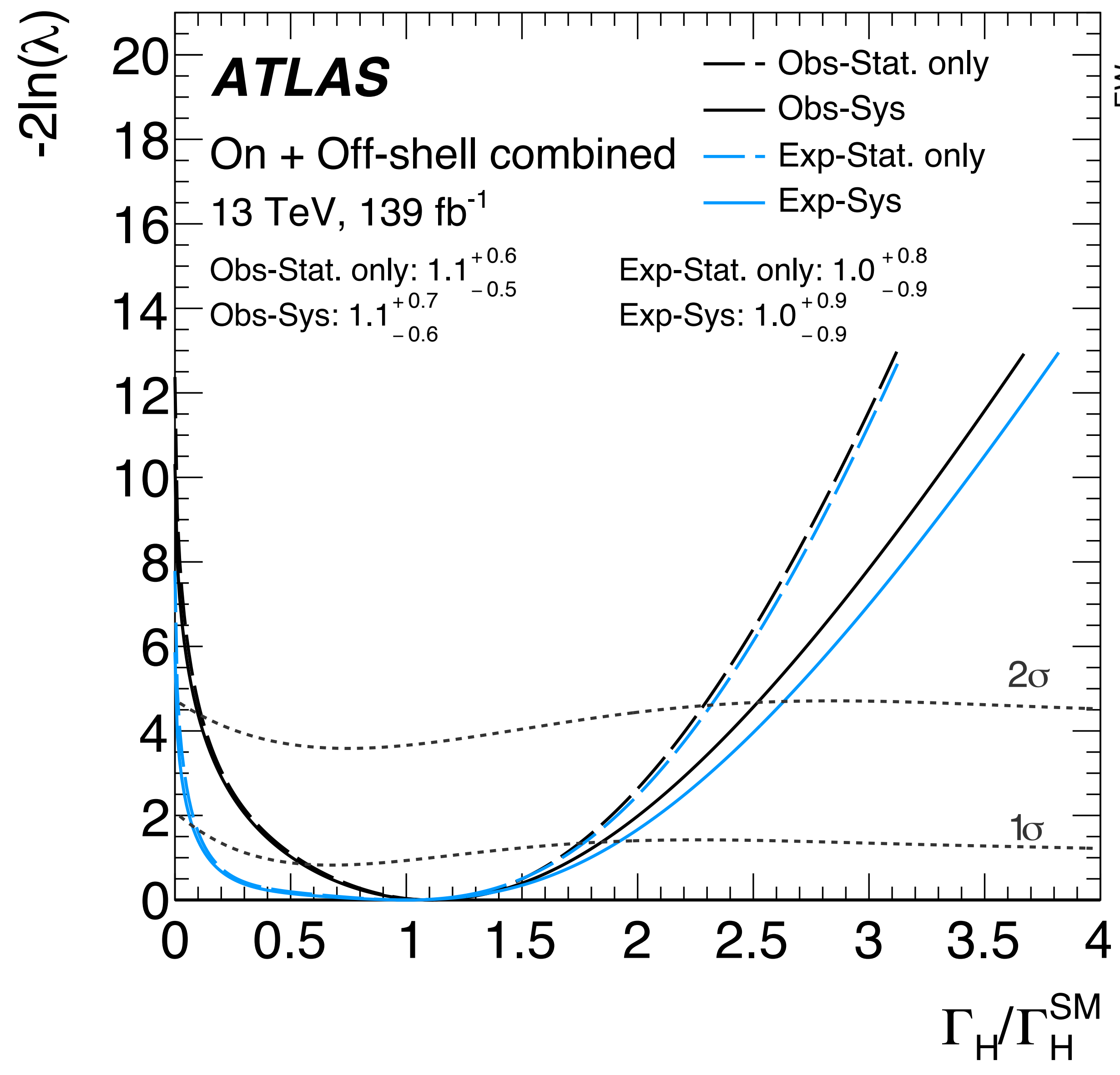

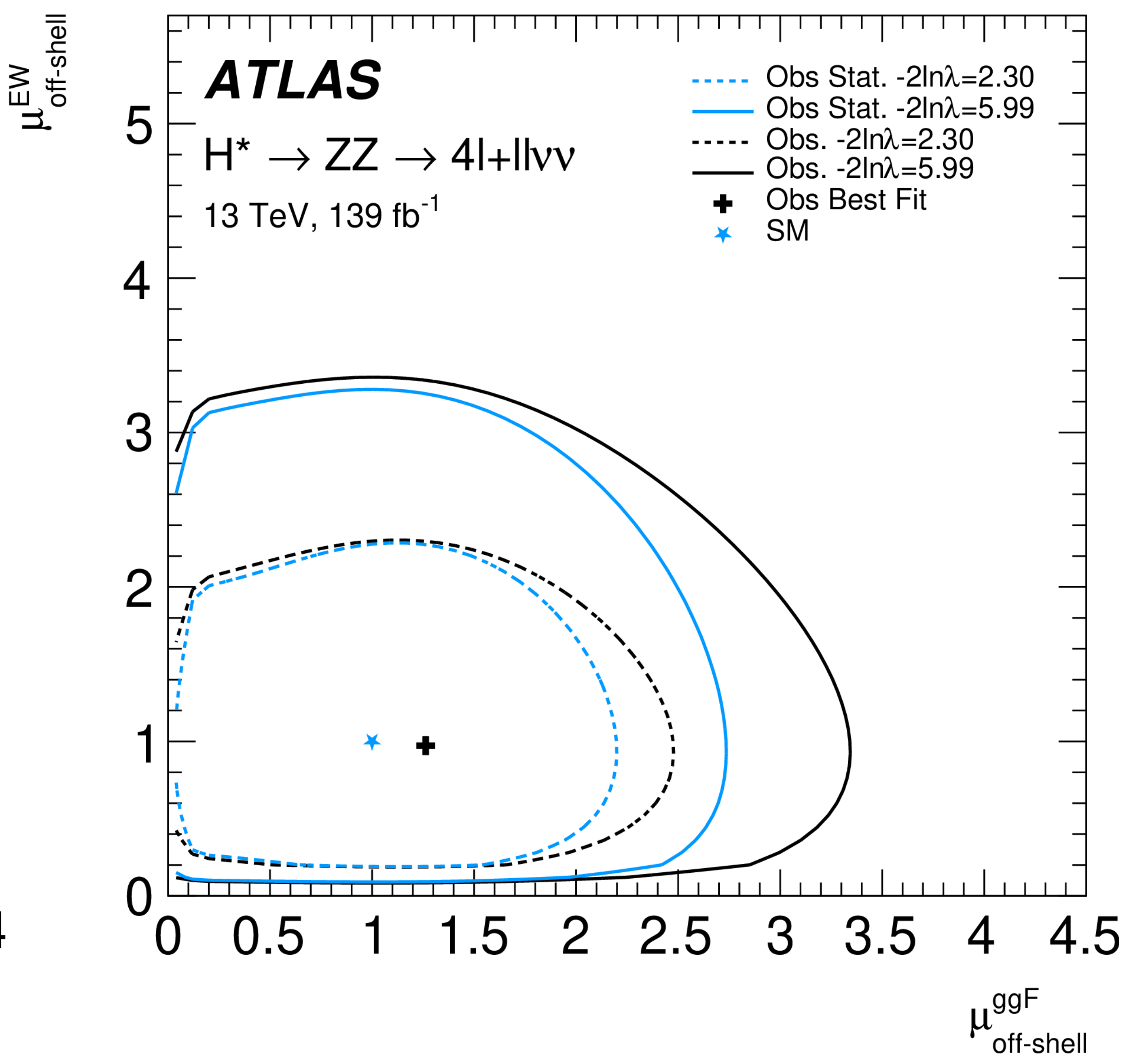

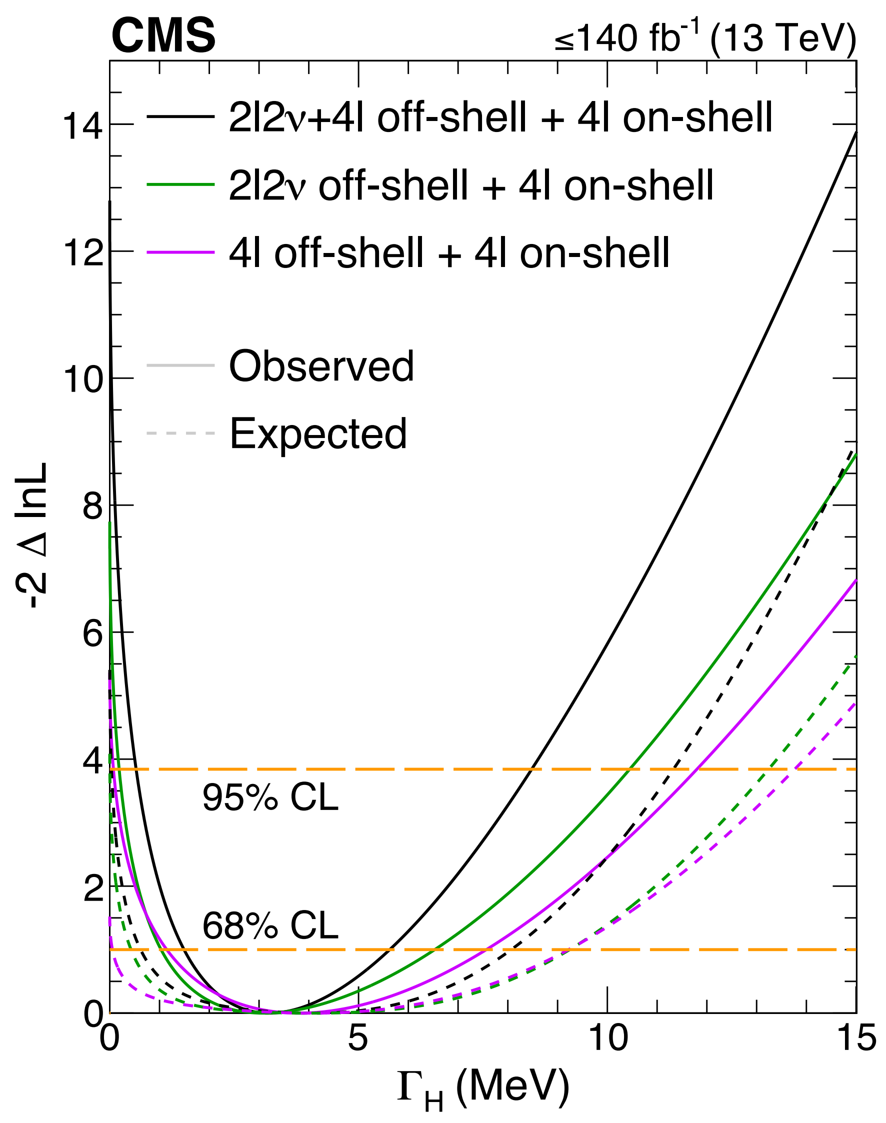

ATLAS 95%CL limits:

$\mu_{\text{off}} < 2.4 \quad \Gamma_H/\Gamma_H^{\text{SM}} < 2.6$

Off-shell region:

$m_{ZZ} > 220$ GeV

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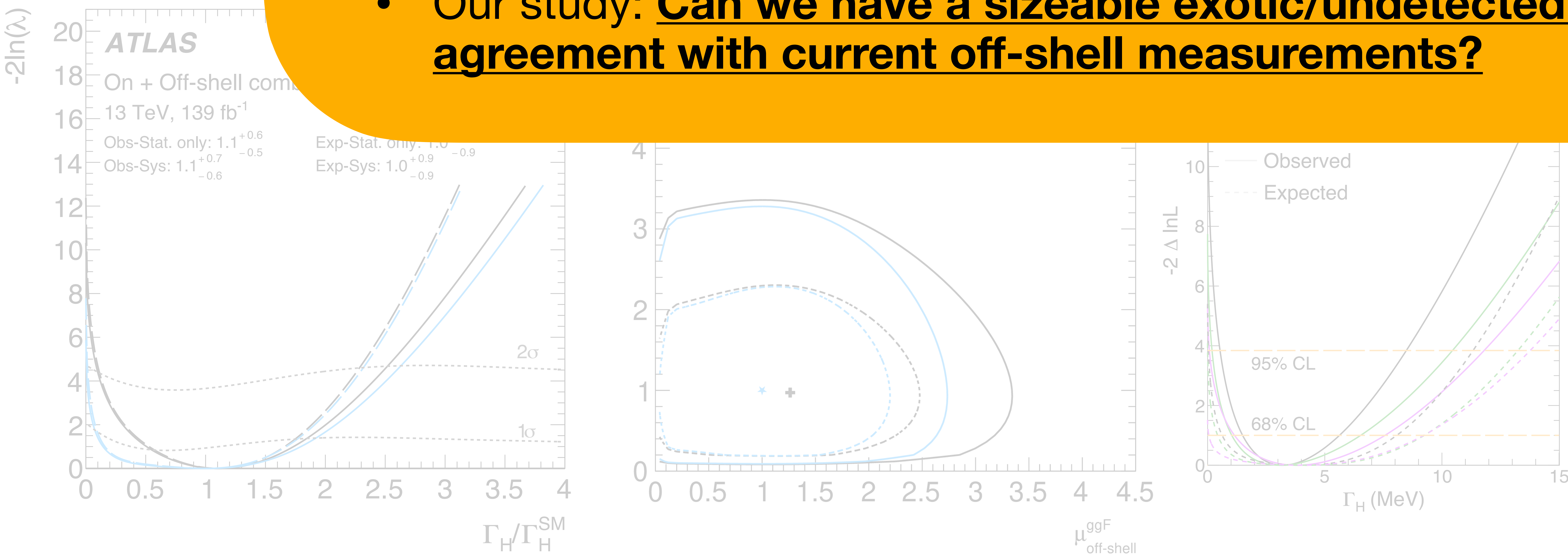
$$\kappa_{i,\rm off} = \kappa_{i,\rm on}$$

$$\mu_{\rm off}(gg \to H \to ZZ) = \frac{\sigma(gg \to H \to ZZ)}{\ldots(\ldots \to H \to ZZ)}$$

- Various studies for BSM in off-shell region, e.g [Logan `14] [Englert, Soreq, Spannowsky `14] [Gonçalves, Han, Mukhopadhyay `18]
- Our study: **Can we have a sizeable exotic/undetected Higgs width but in agreement with current off-shell measurements?**



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$$m_{ZZ} > 220 \text{ GeV}$$

Relaxing the indirect width measurement assumption

- Focus on off-shell $gg \to H \to ZZ$ with only top loop $\Longrightarrow$ **relevant Higgs couplings:** κ_t, κ_Z

- To allow for a larger Higgs width we need to **decrease** the off-shell rate

$$\mu_{\rm on} \simeq \frac{\kappa_t^2 \kappa_Z^2}{\underbrace{\Gamma_H/\Gamma_H^{\rm SM}}} \simeq 1 \qquad\qquad \mu_{\rm off} \simeq \left(\kappa_t^2 \kappa_Z^2 + \text{ off-shell effects}\right) \leq 2.4$$

Enhanced from exotic/undetected width

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- Allow deviations on κ_t, κ_Z and try to reduce off-shell rate by introducing scalars:

➡ Propagating BSM scalar $gg \to S \to ZZ$

➡ Modification of the Higgs gluon-fusion $gg \to H$ due to a BSM coloured scalar

➡ Modification the Higgs propagator with a scalar-singlet loop contribution

(last two: one-loop level)

Propagating Scalar Singlet in the ZZ channel

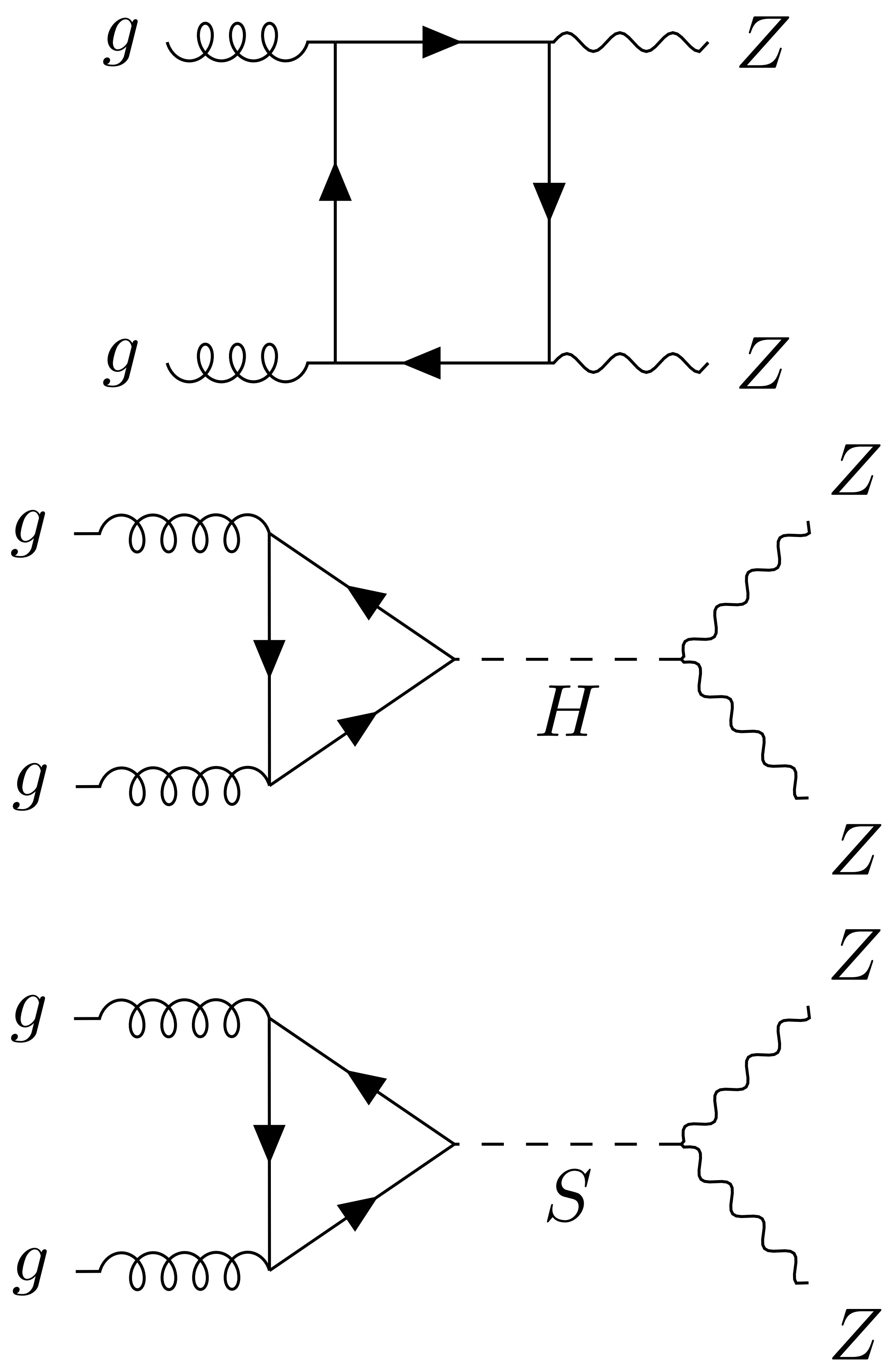
- Simple extension with a scalar singlet coupled to top-quarks and Z boson:

$$\mathcal{L} \supset -C_{Stt}\frac{y_t}{\sqrt{2}}\bar{t}St + C_{SZZ}\frac{e^2 v}{4c_W^2 s_W^2}Z_\mu Z^\mu S$$

- Unitarity of $t\bar{t} \to ZZ$ channel requires the sum rule: [Logan `14]

$$\kappa_t \kappa_Z + C_{Stt}C_{SZZ} = 1$$

- Model implemented with FeynRules and NLOCT for simulations with MadGraph5_aMC@NLO



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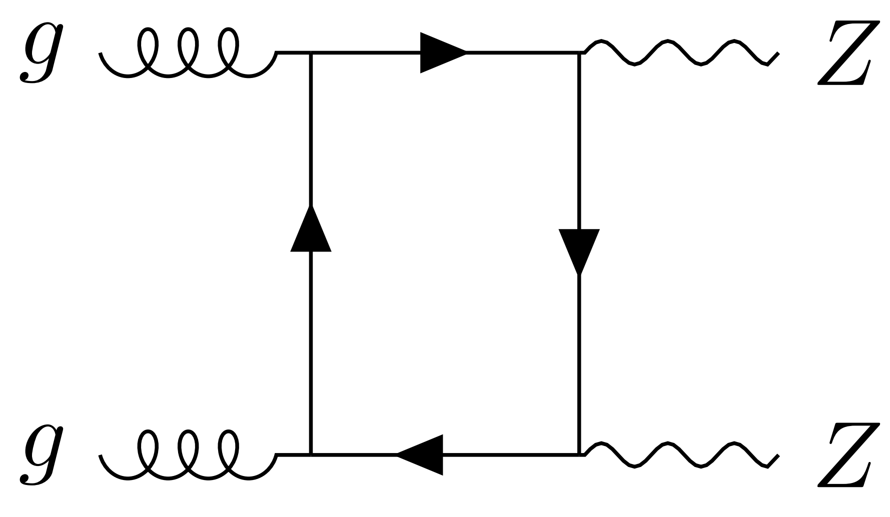

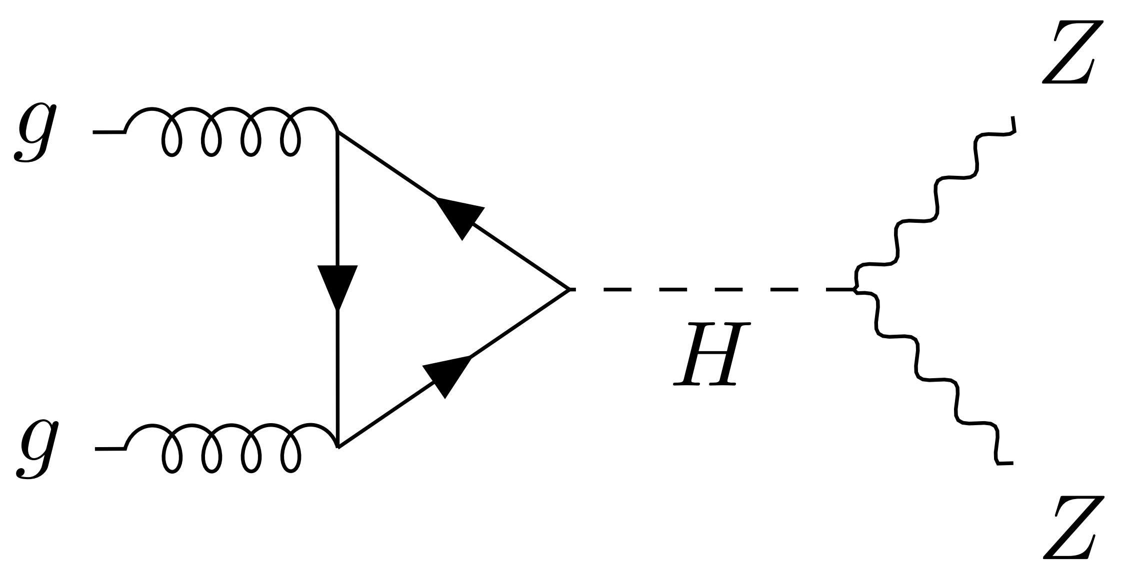

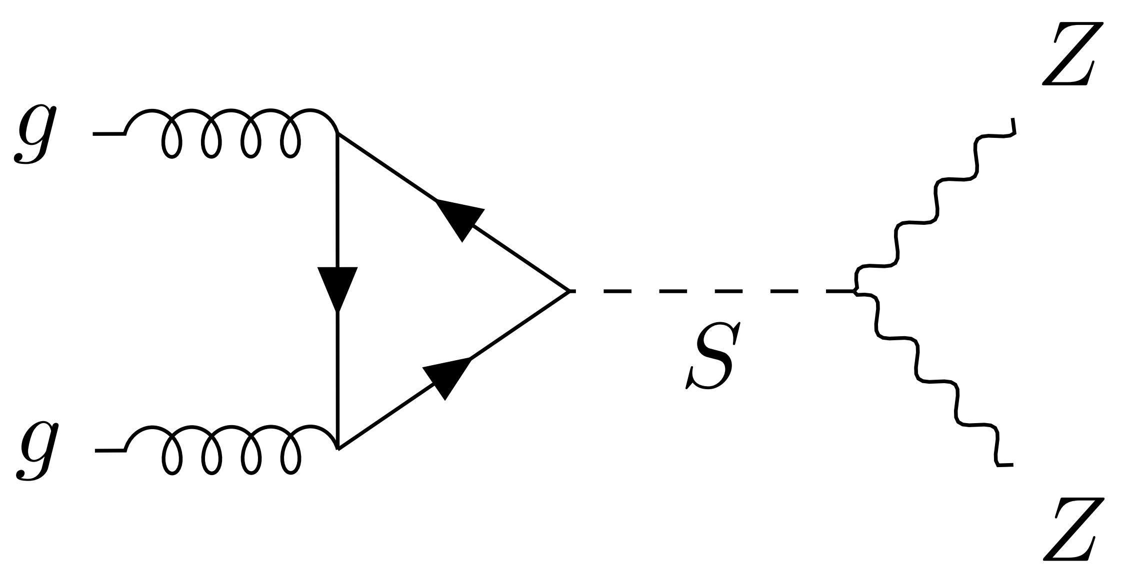

Parameterised cross section:

$$\begin{aligned} d\sigma_{gg\to ZZ}(\kappa_t\kappa_Z, C_{Stt}C_{SZZ}) = {} & \\ & d\sigma_{(0,0)} + \kappa_t\kappa_Z d\sigma_{(2,0)} + \kappa_t^2\kappa_Z^2 d\sigma_{(4,0)} \\ & + C_{Stt}C_{SZZ}d\sigma_{(0,2)} + \kappa_t\kappa_Z C_{Stt}C_{SZZ}d\sigma_{(2,2)} \\ & + C_{Stt}^2 C_{SZZ}^2 d\sigma_{(0,4)} \end{aligned}$$

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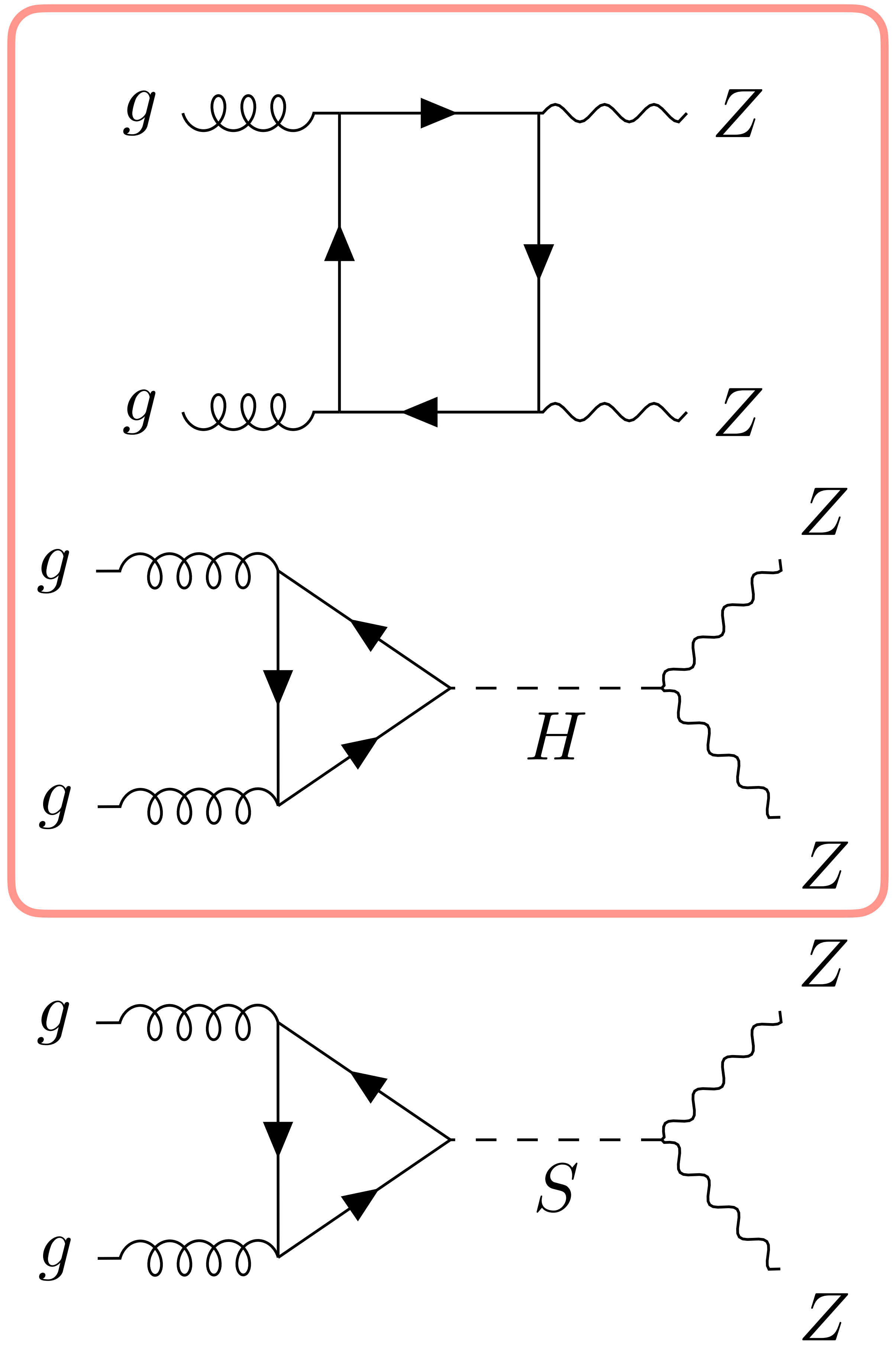

Parameterised cross section:

SM with coupling modifiers

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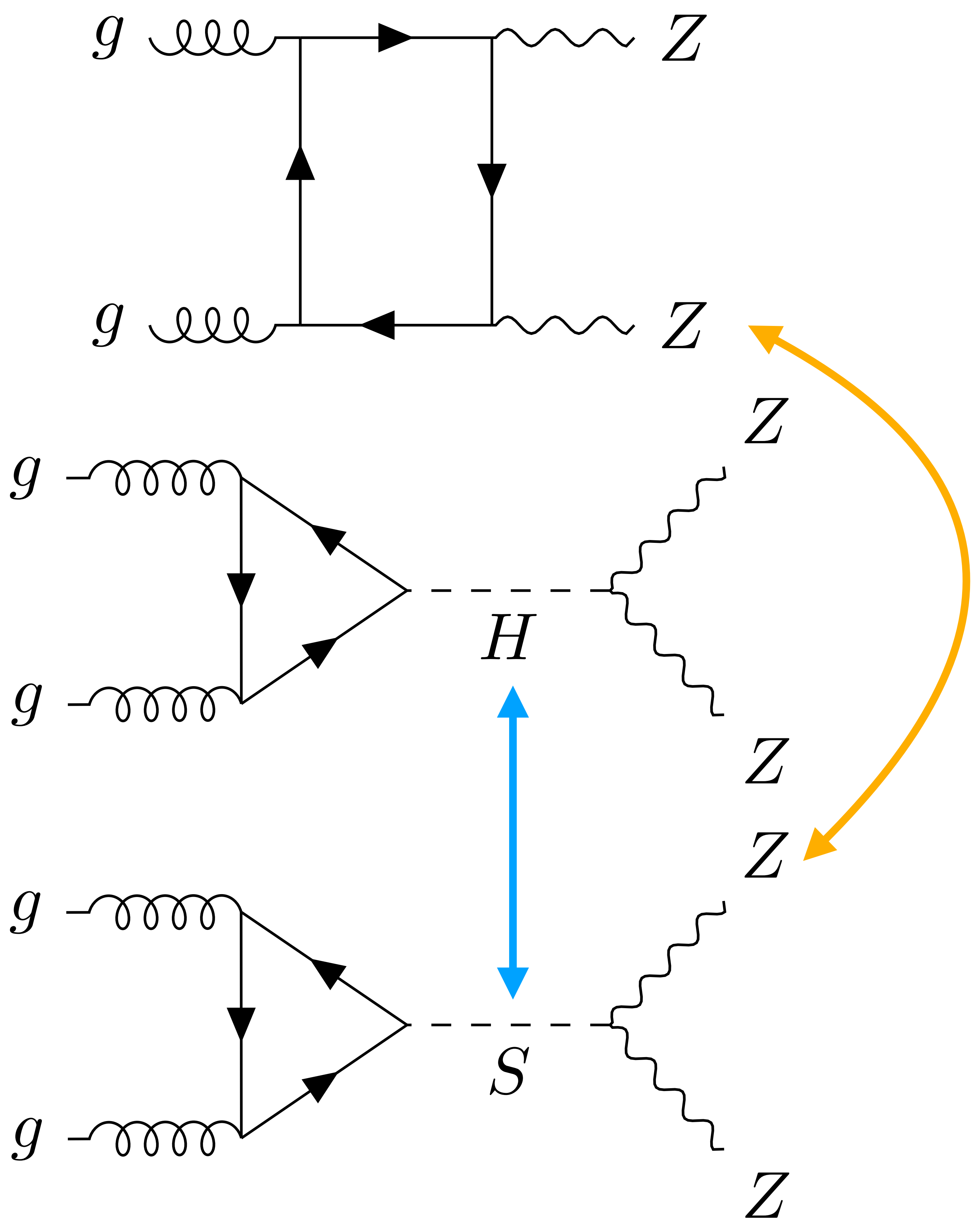

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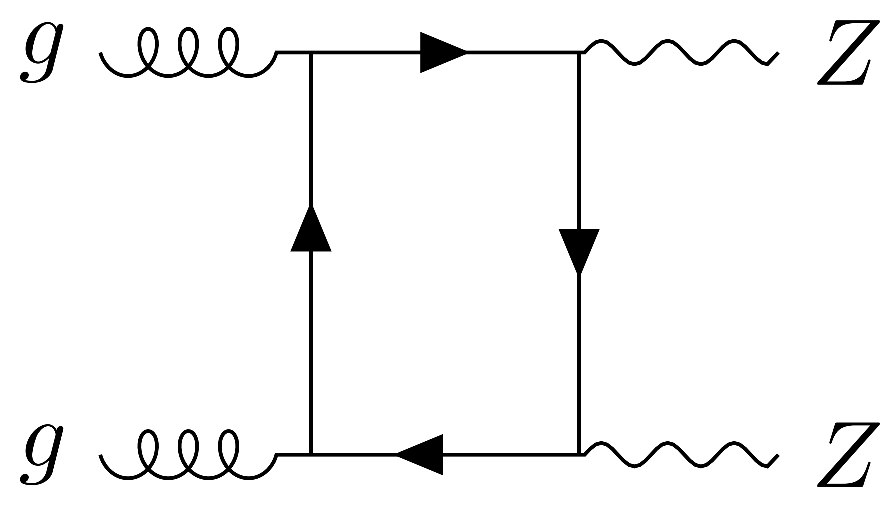

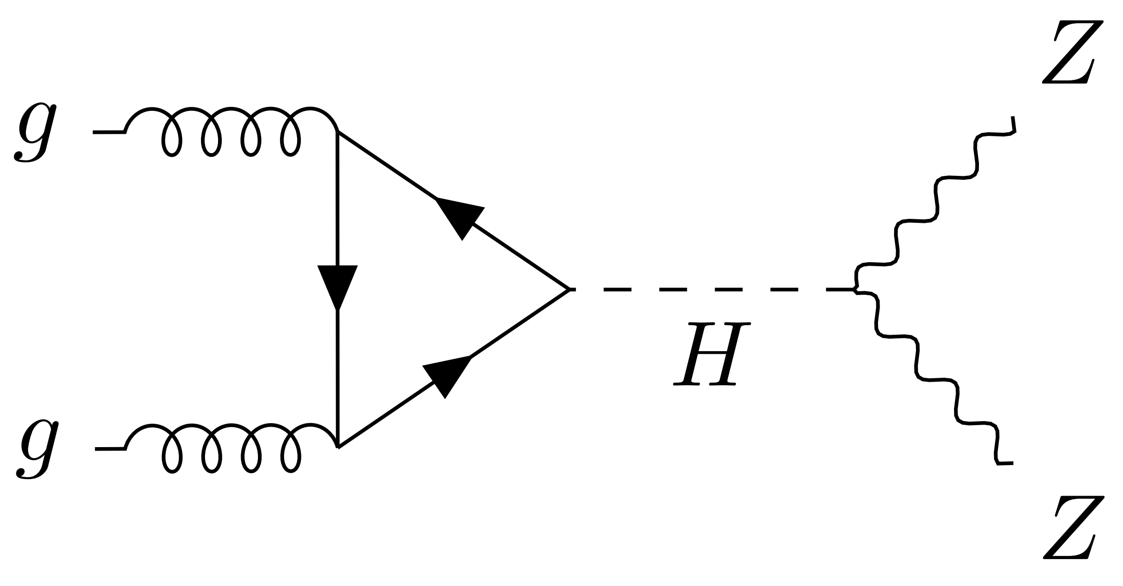

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$$+ \; C_{Stt} C_{SZZ} d\sigma_{(0,2)} + \kappa_t \kappa_Z C_{Stt} C_{SZZ} d\sigma_{(2,2)}$$

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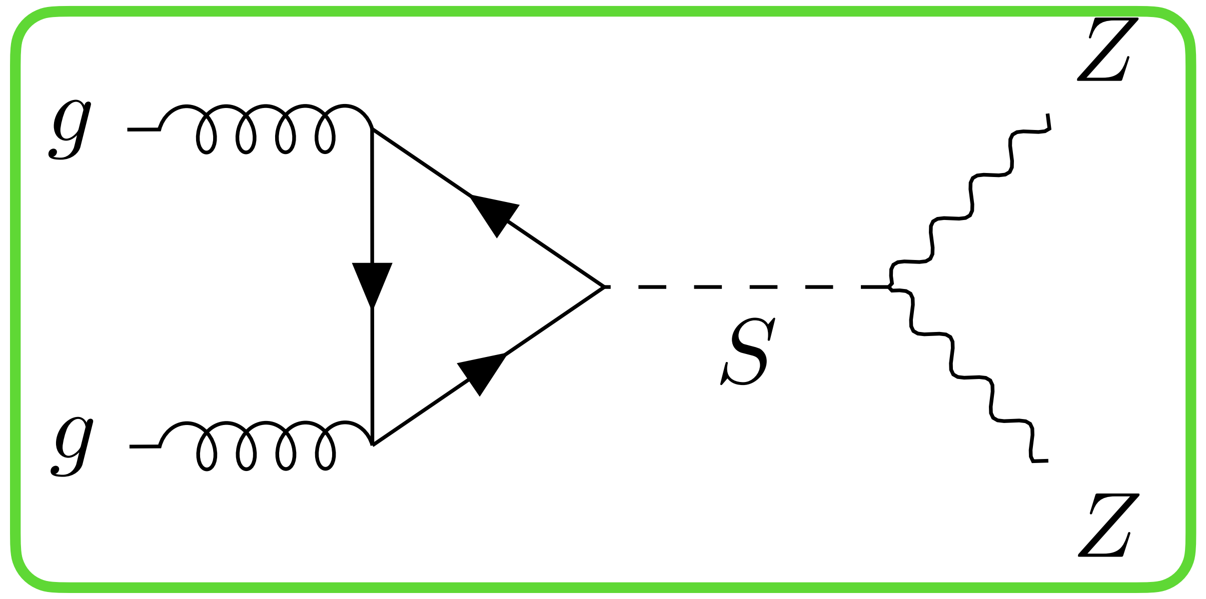
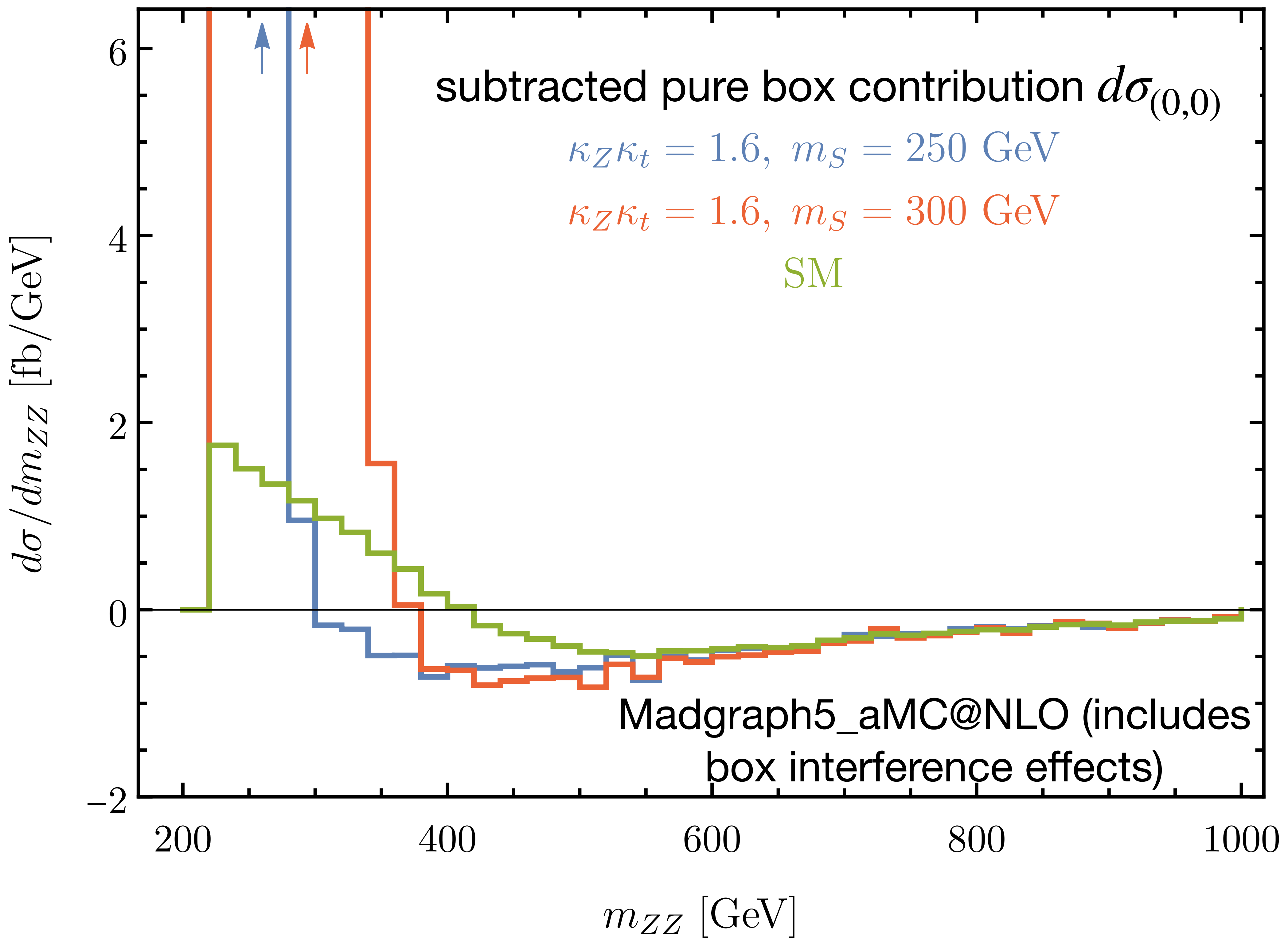
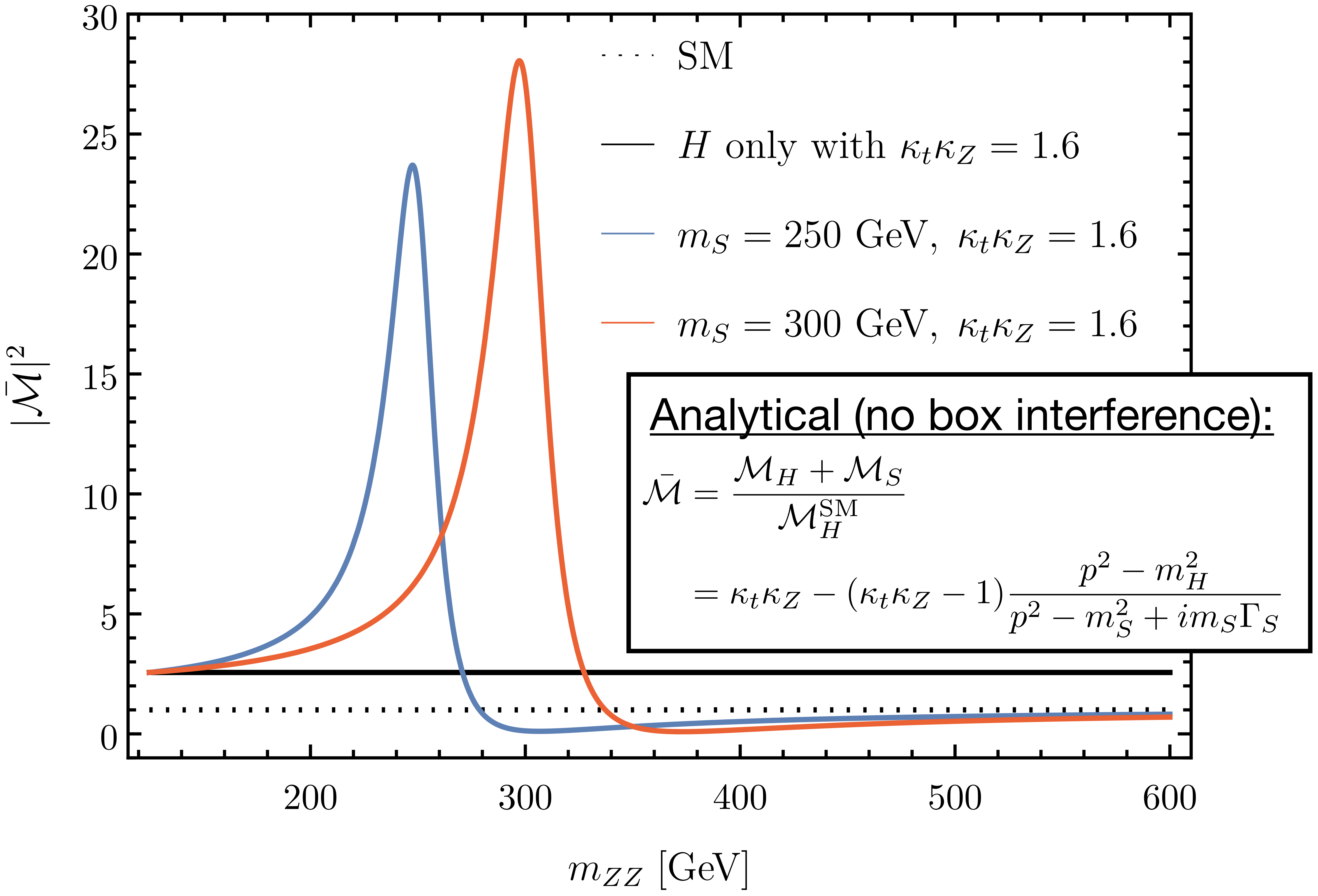


Propagating Scalar Singlet in the ZZ channel

- $C_{SZZ}C_{Stt}$ is replaced by $\kappa_Z\kappa_t$ using the sum rule
- Destructive interference could decrease the off-shell rate depending on m_S, κ_t, κ_Z [Logan `14]
- Simulations at $gg \to ZZ$ level with $m_{ZZ} > 220$ GeV
- Size and location of resonance is important

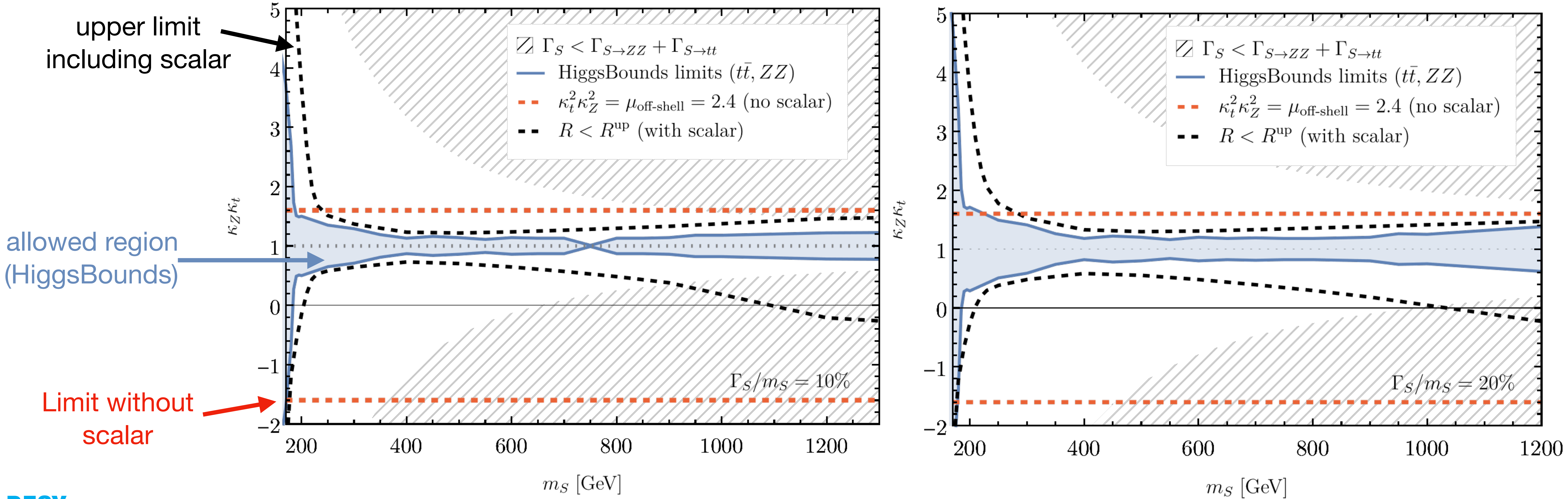




Impact of propagating scalar on Higgs width

- To check compatibility with $\mu_{\text{off}} < 2.4$, define the ratio: $$R(\kappa_t\kappa_Z, C_{Stt}C_{SZZ}) = \frac{\sigma_{gg\to ZZ}(\kappa_t\kappa_Z, C_{Stt}C_{SZZ})}{\sigma^{\text{SM}}_{gg\to ZZ}}$$
- Upper limit on R from ATLAS off-shell signal strength: $$R^{\text{up}} = \frac{\sigma_{(0,0)} + \sqrt{\mu_{\text{off}}^{\text{up}}}\,\sigma_{(2,0)} + \mu_{\text{off}}^{\text{up}}\,\sigma_{(4,0)}}{\sigma_{(0,0)} + \sigma_{(2,0)} + \sigma_{(4,0)}} = 3.4$$
- Compare with limits from **HiggsBounds*** assuming only decays to top-quarks and Z bosons

*modified to include [CMS-PAS-HIG-24-002]



Impact of propagating scalar on Higgs width

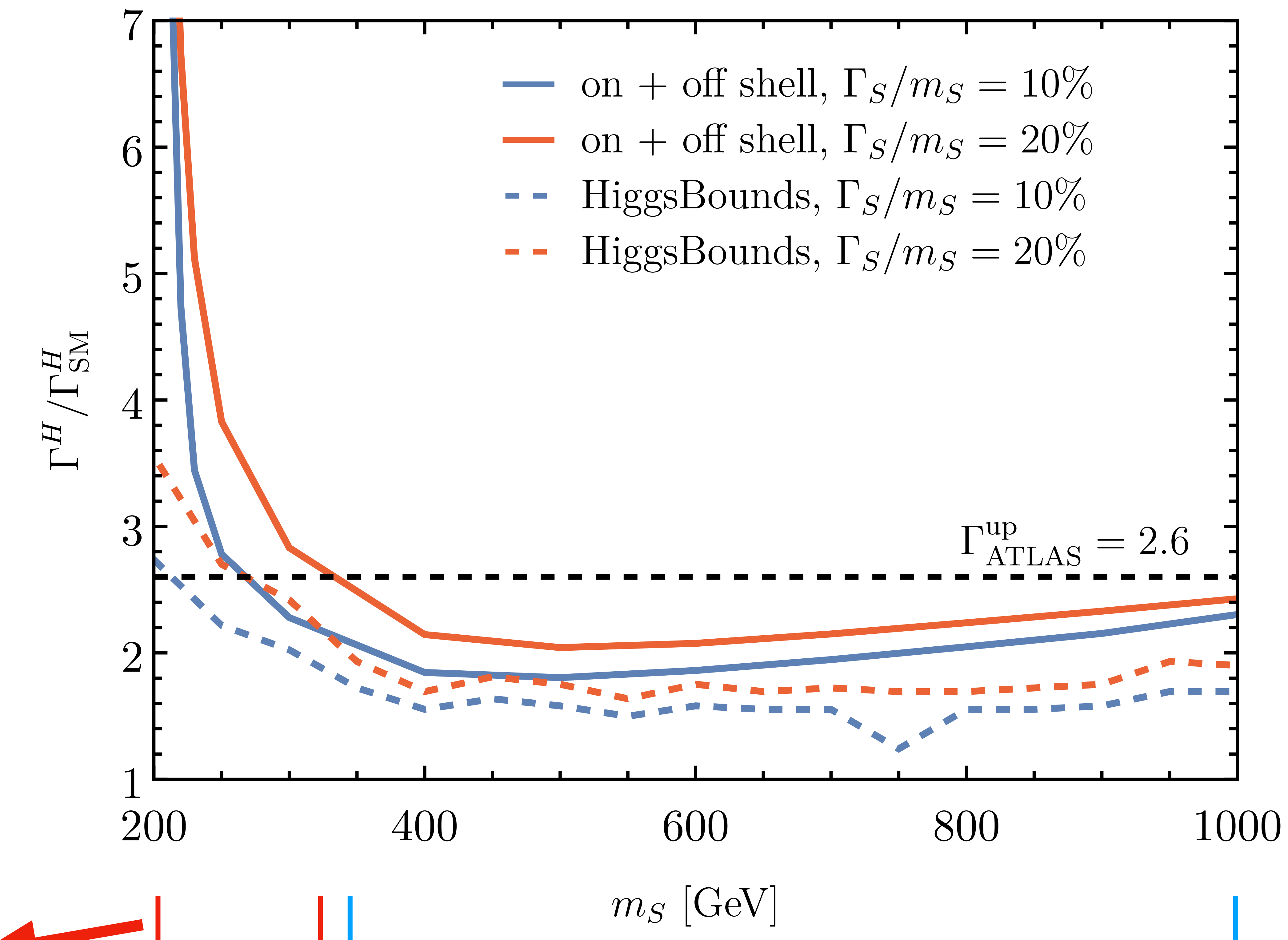
- Assuming no impact on on-shell signal strength from S, we can use:

$$\mu_{\text{on}} = \frac{\kappa_t^2 \kappa_Z^2}{\Gamma_H / \Gamma_H^{\text{SM}}}$$

- Experimental bounds on on-shell signal strength:

$$\mu_{\text{on}}^{\text{ATLAS}} = 1.01^{+0.23}_{-0.20}$$

- Re-interpreted upper bound on $\kappa_t \kappa_Z$ as upper bound on Higgs width using on-shell results



- For low masses the resonance is outside the off-shell region and interference decreases the rate → weaker bound on Γ_H
- HiggsBounds limits require $\Gamma^H/\Gamma^H_{\text{SM}} \lesssim 4$ (but are model-dependent)

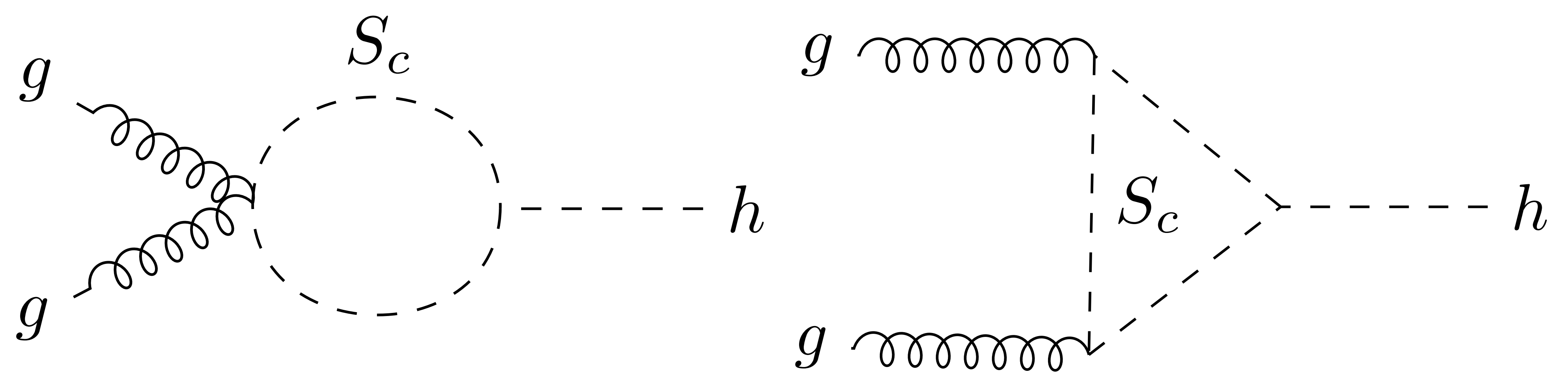
For heavy scalars the presence of a resonance increases the off-shell rate and results on a stronger bound on Γ_H

Gluon fusion modification: coloured scalar

- Investigate simple extension with coloured scalar S_c:

$$\mathcal{L} \supset D_\mu S_c D^\mu \bar{S}_c - m_{S_c}^2 S_c \bar{S}_c + \lambda_{S_c} \Phi^\dagger \Phi S_c^\dagger S_c$$

leads to gluon-fusion modification



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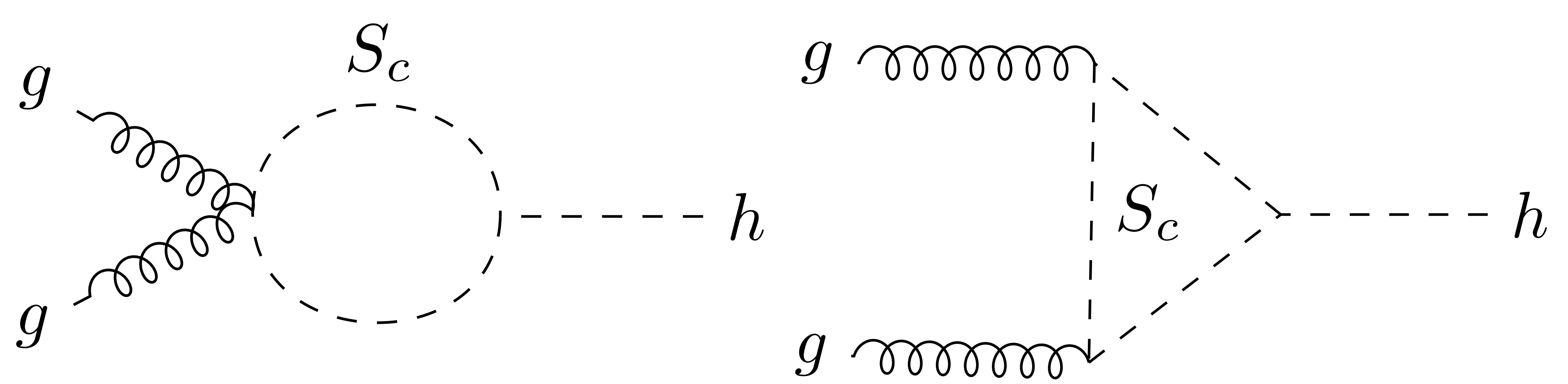

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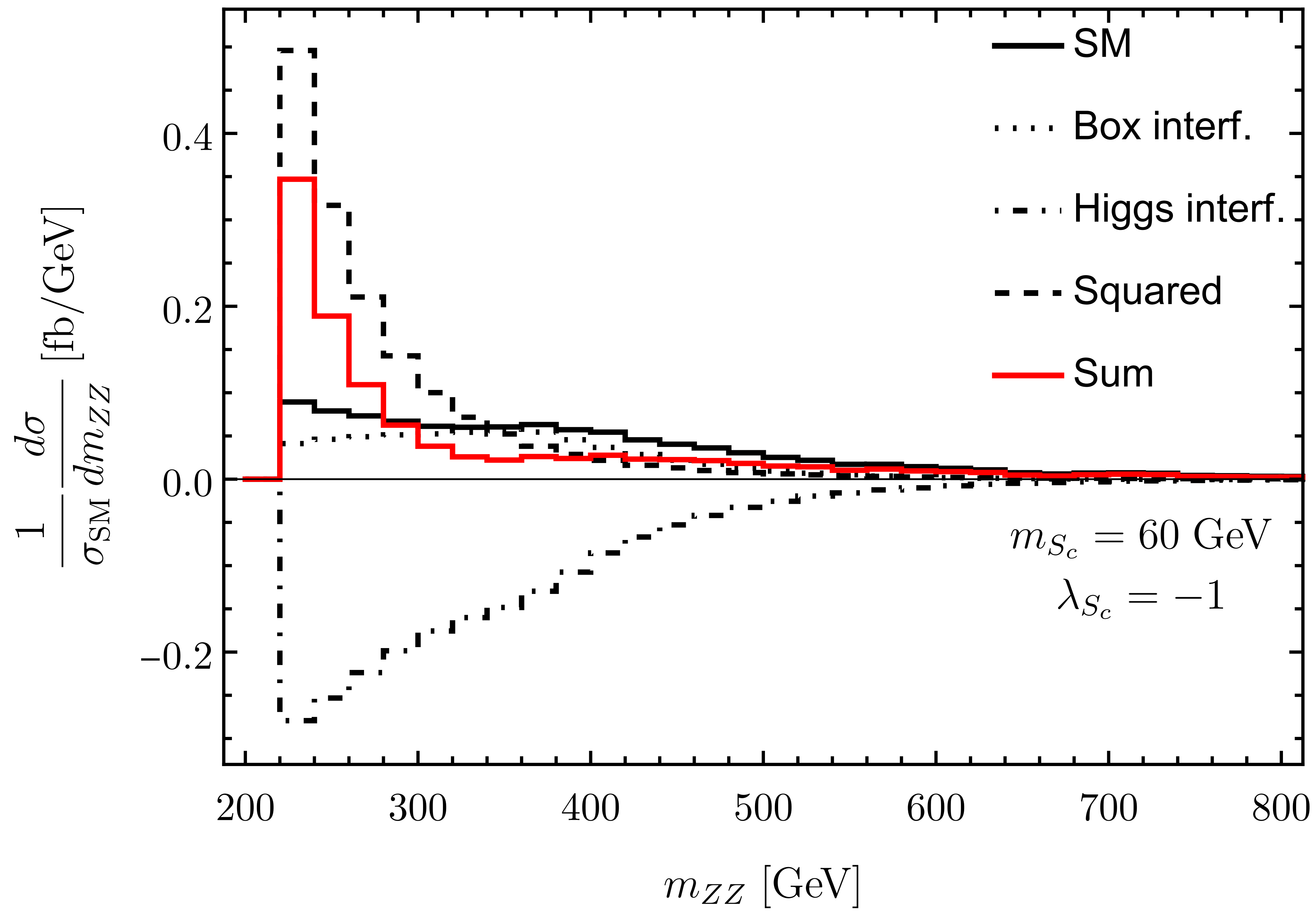
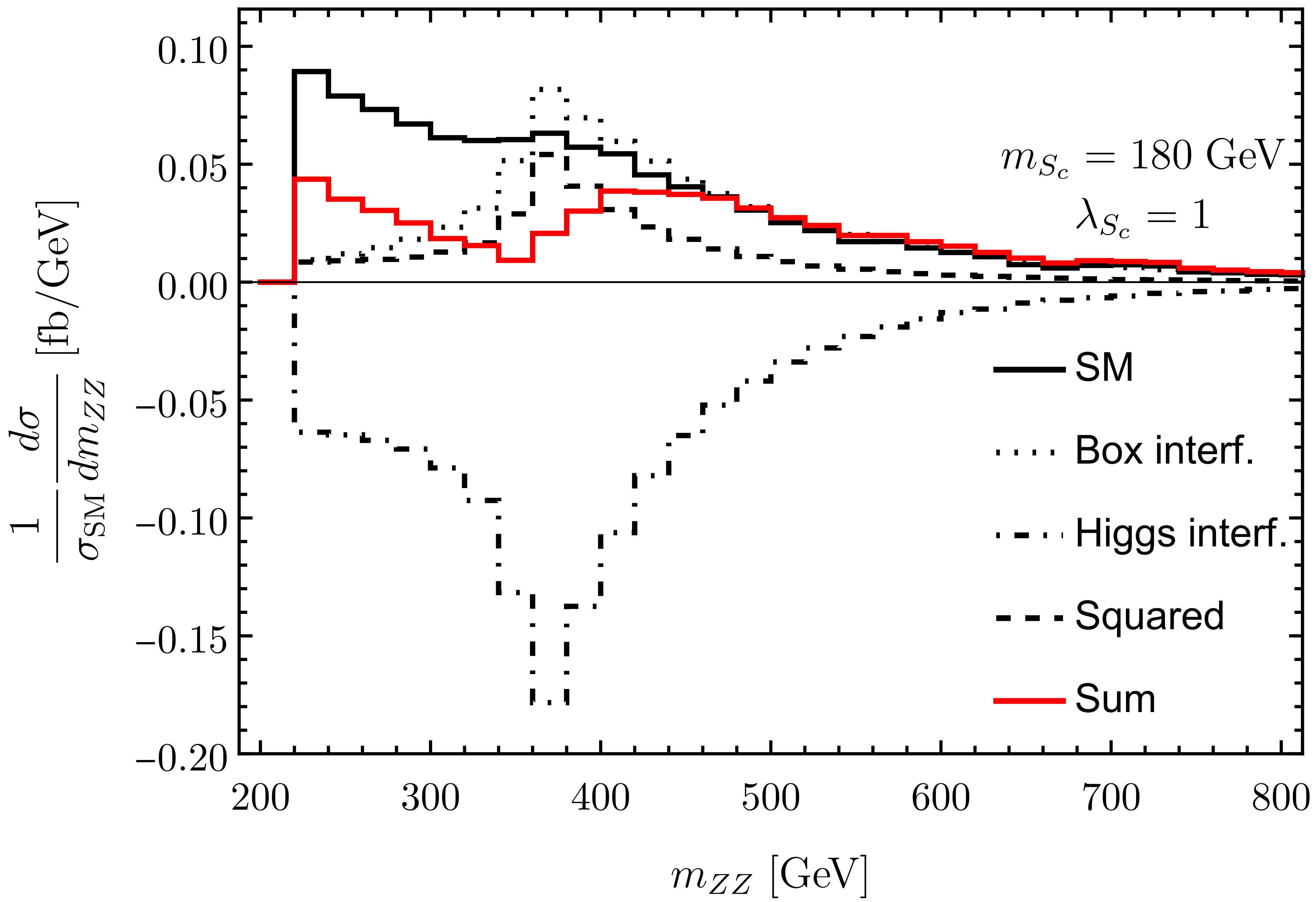
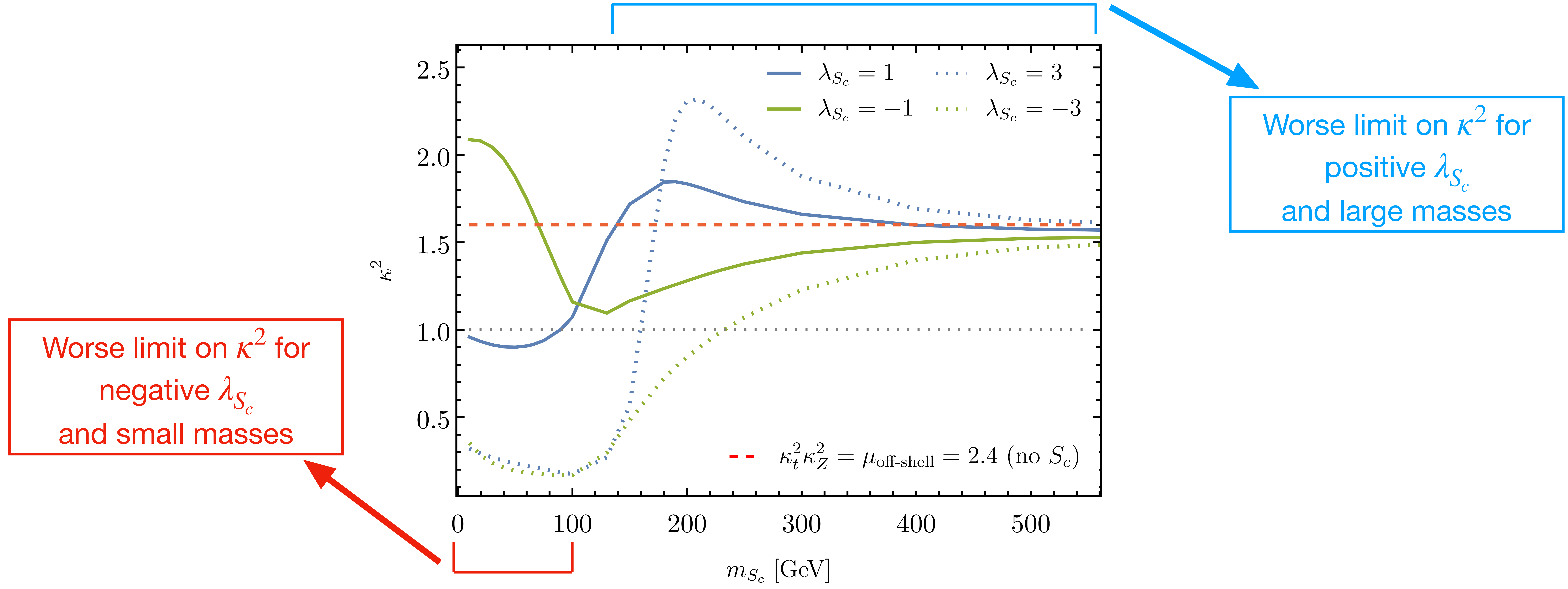




Impact of propagating scalar on Higgs width

- Define ratio similar to previous case: $R(\kappa_t, \kappa_Z, \lambda_{S_c}) = \dfrac{\sigma_{gg\to ZZ}(\kappa_t, \kappa_Z, \lambda_{S_c})}{\sigma^{\text{SM}}_{gg\to ZZ}}$
- **Upper limits** on $\kappa_t = \kappa_Z = \kappa$ from $R(\kappa, \kappa, \lambda_{S_c}) < R^{\text{up}}$

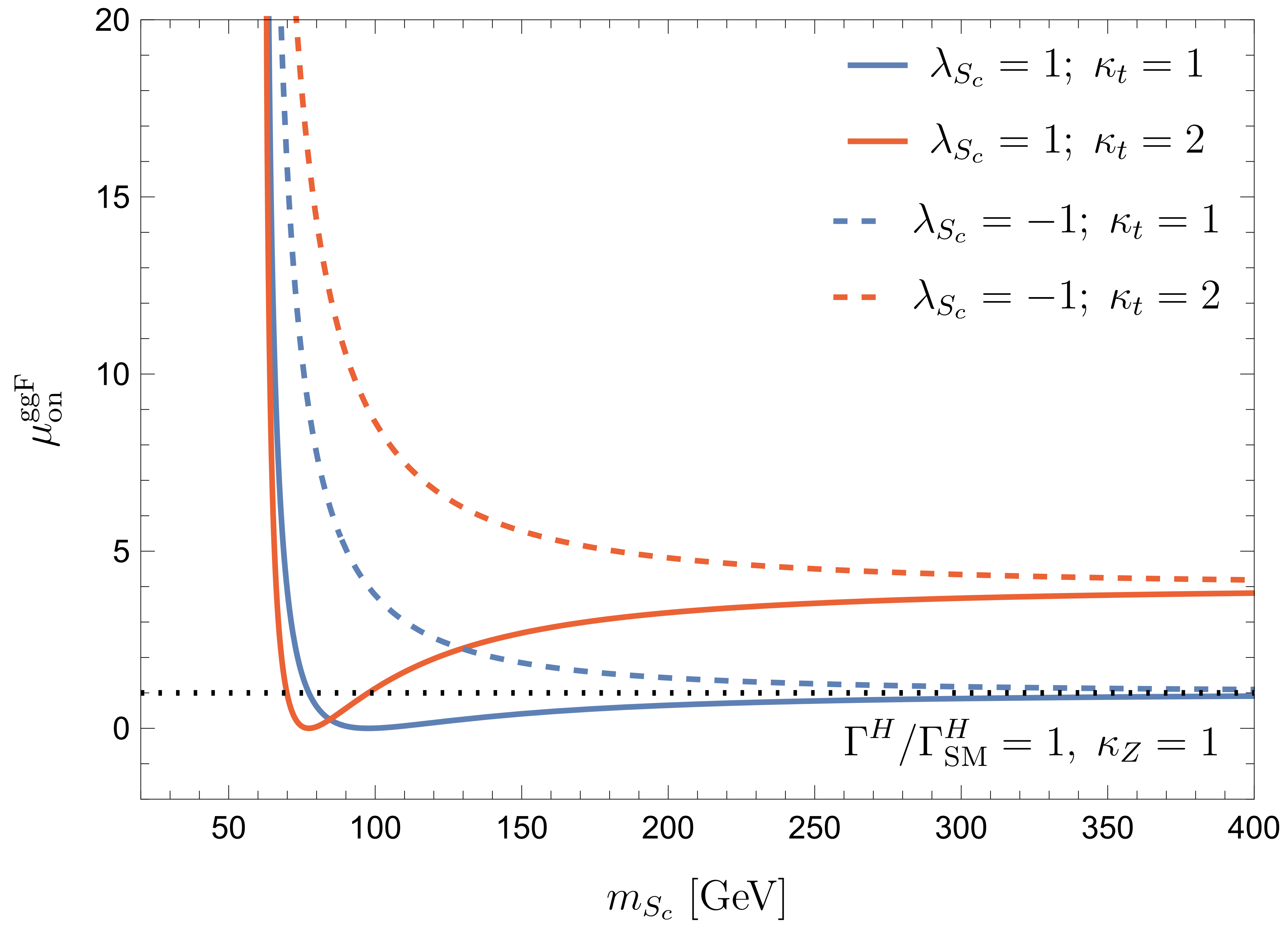


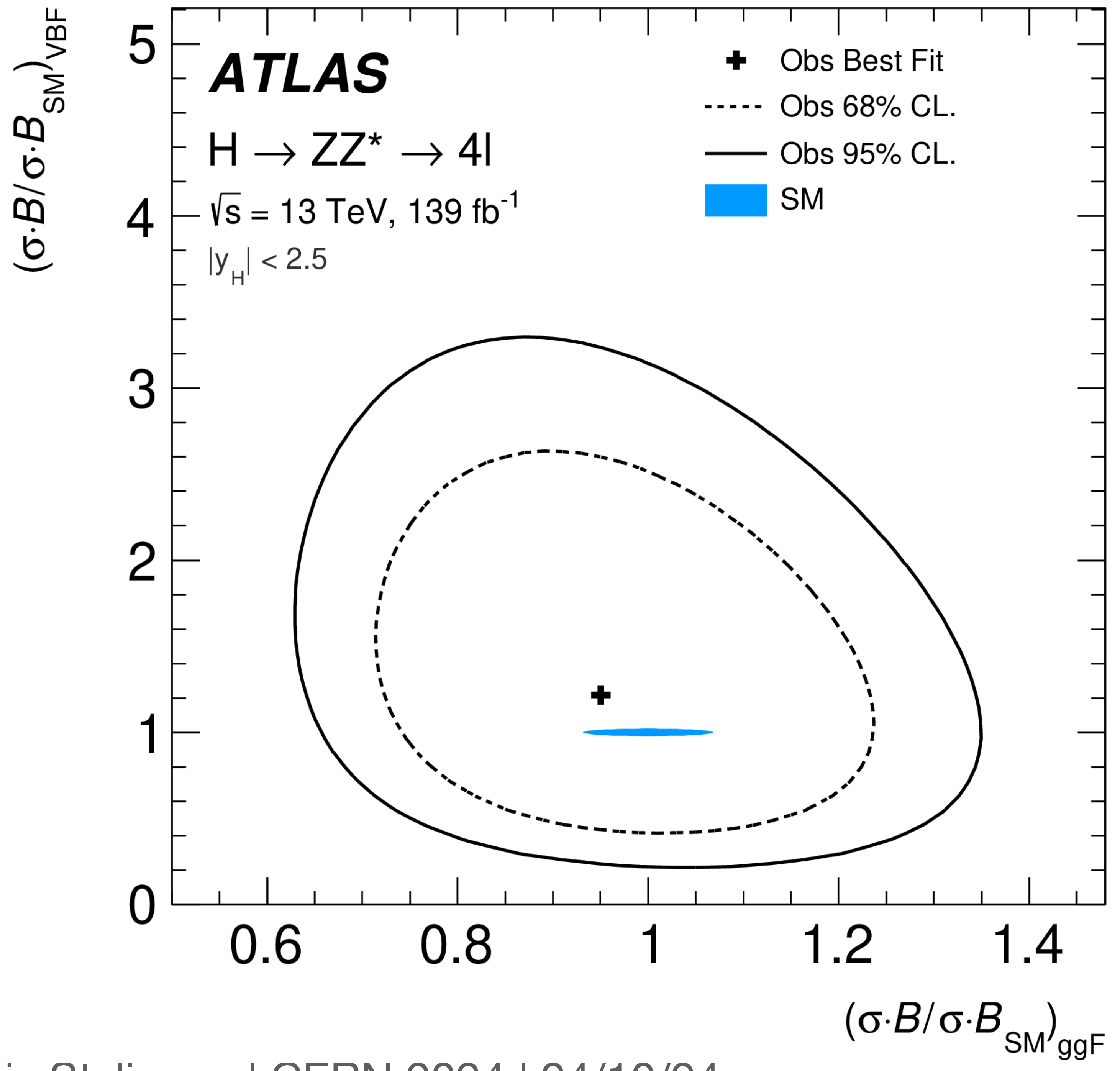
Coloured Scalar: on-shell

- Connecting to Higgs width more complicated:

$$\mu_{\text{on}}^{\text{ggF}} = \frac{\kappa_V^2}{\Gamma^H/\Gamma^H_{\text{SM}}} \left| \kappa_t + \frac{\lambda_{S_c} v^2 \left[1 + \tau_{S_c} f(\tau_{S_c})\right]}{m_H^2 \left[1 + (\tau_t - 1) f(\tau_t)\right]} \right|^2$$

$$f(\tau_i) = \begin{cases} \arcsin^2 \tau_i^{-1/2} & \tau_i > 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi\right]^2 & \tau_i < 1 \end{cases} \quad \text{for } \tau_i = 4m_i^2/m_H^2$$





- VBF on-shell signal strength: $\mu_{\text{on}}^{\text{VBF}} = \frac{\kappa_V^4}{\Gamma_H/\Gamma_H^{\text{SM}}}$

- We use our allowed range of κ^2 and require that the on-shell signal strengths lie within the ATLAS $95\ \%$ CL bounds

[ATLAS 2004.03447]

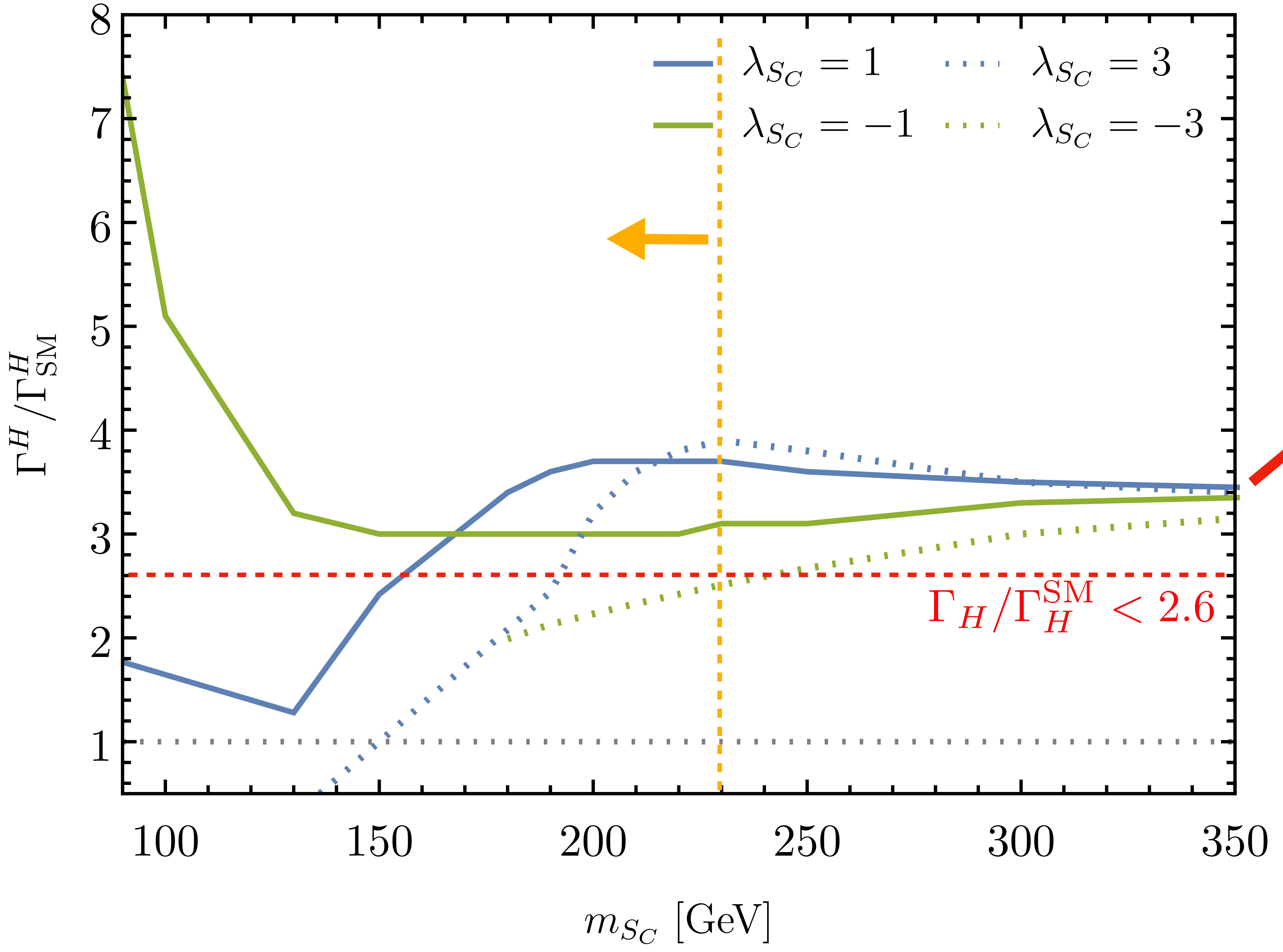
Coloured Scalar: impact on Higgs width

- We obtain the upper bound on the total Higgs width compatible with both on-shell and off-shell results

Masses smaller than ~230 GeV could be excluded from $pp \to S_c S_c$, depending on the decay modes

[CDF 1303.2699]
[ATLAS 1210.4826]

Mass range that is not shown results in large on-shell signal-strengths incompatible with experimental limits

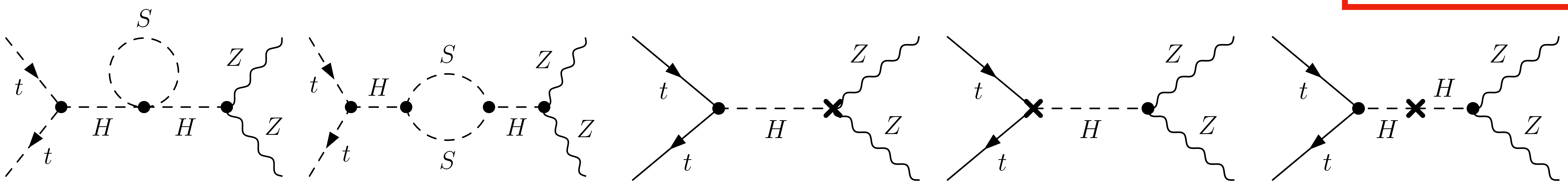


Overall weaker limit than before, **but** this is because we do not use the combined on-shell signal strength

Loop modification of Higgs propagator: Higgs portal

- Scalar singlet modifying the Higgs propagator at 1-loop through Higgs portal coupling:

$$\mathcal{L} \supset -\lambda_S S^2 \Phi^\dagger \Phi$$

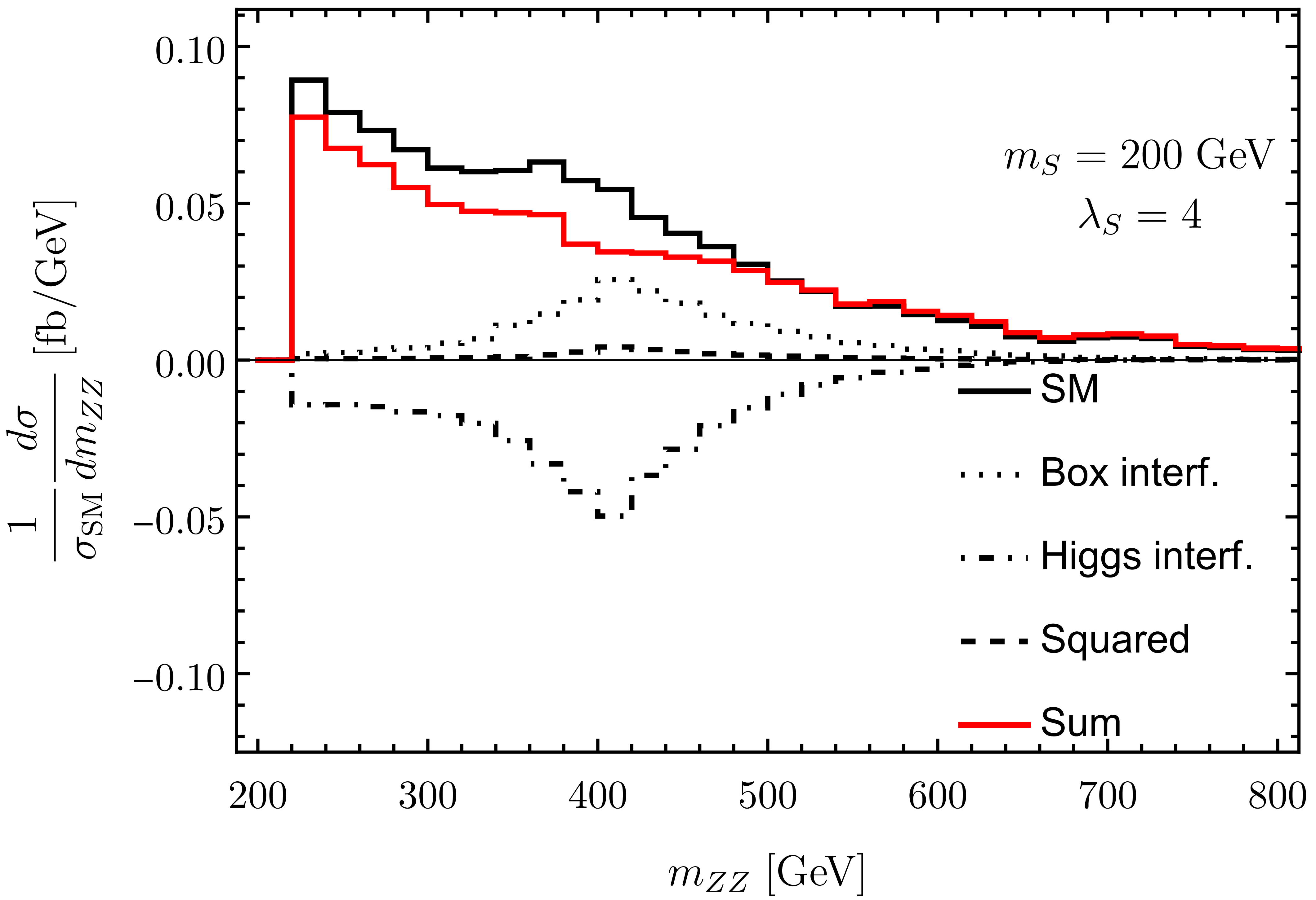


- Higgs amplitude $gg \to H \to ZZ$ modification factor:

$$\bar{\mathcal{M}} = \frac{\mathcal{M}_H + \mathcal{M}_S}{\mathcal{M}_H^{\rm SM}} = 1 + \frac{\lambda_S^2 v^2}{8\pi^2(p^2 - m_H^2)} \times \left[B_0(p_H^2, m_S^2, m_S^2) - {\rm Re}B_0(m_H^2, m_S^2, m_S^2)\right]$$

- Introduced in UFO model as form-factor in order to calculate $gg \to ZZ$ process with Higgs/box interference

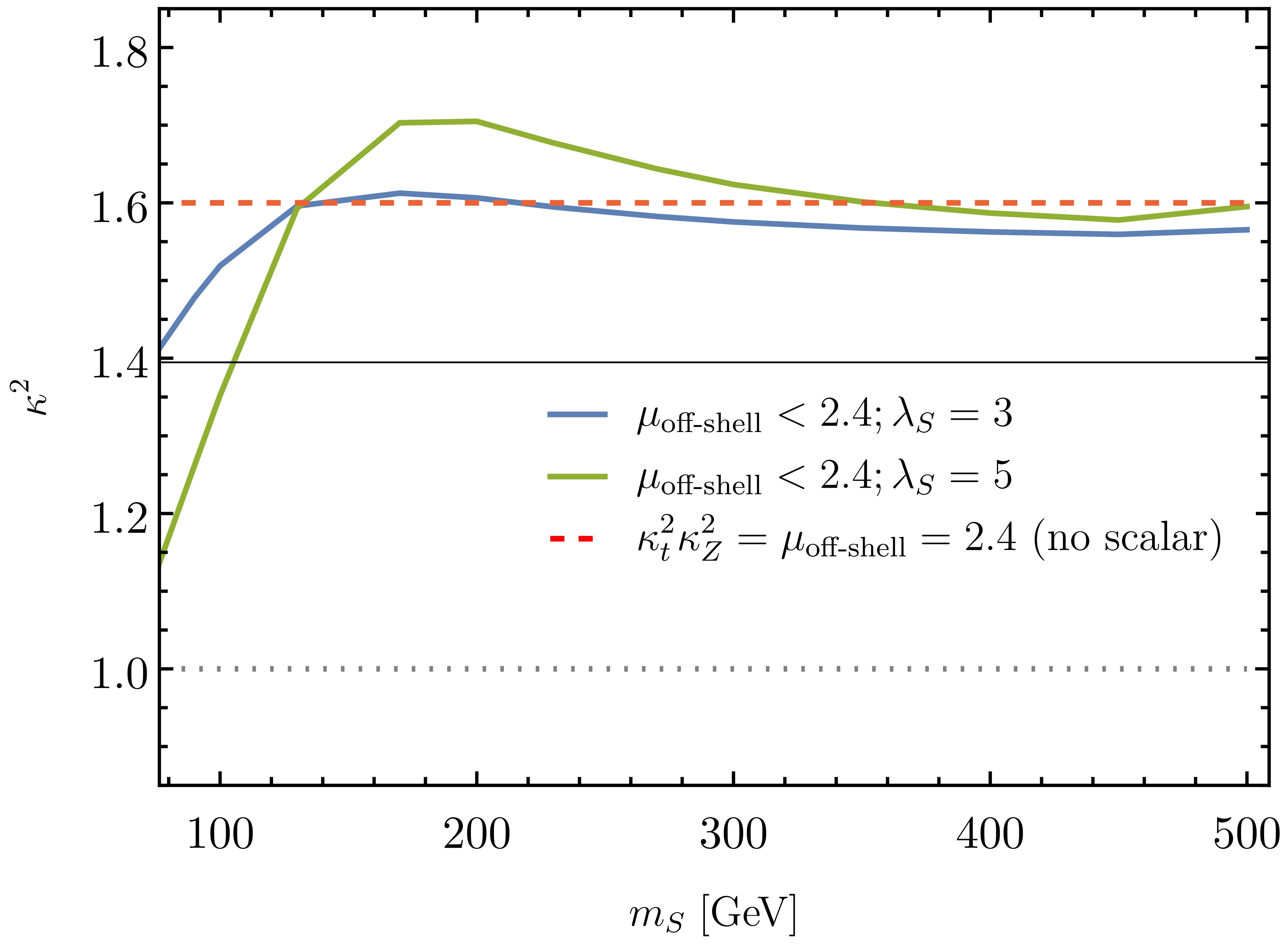
- Similar cross section parameterisation as before



Impact of propagating scalar on Higgs width

- Upper limits similar to previous cases: $R(\kappa\kappa, \lambda_S) = \frac{\sigma_{gg\to ZZ}(\kappa, \kappa, \lambda_S)}{\sigma^{\text{SM}}_{gg\to ZZ}} < R^{\text{up}}$
- Much smaller impact on κ^2 even at relatively large couplings λ_S

We could again use the on-shell signal strength to obtain a limit on Γ_H
→ However, given the small impact on κ^2, we would not get a large impact on Γ_H



Conclusions

- A direct determination of the Higgs width is not possible in the near future
  → need to rely on **indirect bounds** from the off-shell ZZ channel

- Effects in the off-shell $gg \to ZZ$ channel that **decrease** the total rate, could allow for enhanced Higgs couplings and thus a larger Higgs width Γ_H

- We assessed the impact on the Higgs width from three simplified scenarios:

  ➡ An additional propagating scalar $gg \to S \to ZZ$

  ➡ Modification of the Higgs gluon-fusion $gg \to H$ due to a coloured scalar

  ➡ Modification the Higgs propagator with a scalar loop contribution

  } Reduction of off-shell rate from interference effects

- Overall, the indirect Higgs width limit remains robust, except for effects arising from scalars with relatively low masses → **however** searches for such scalars can widen the validity of the Higgs width limit

Conclusions

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- Overall, the indirect Higgs width limit remains robust, except for effects arising from scalars with relatively low masses $\rightarrow$ **however** searches for such scalars can widen the validity of the Higgs width limit

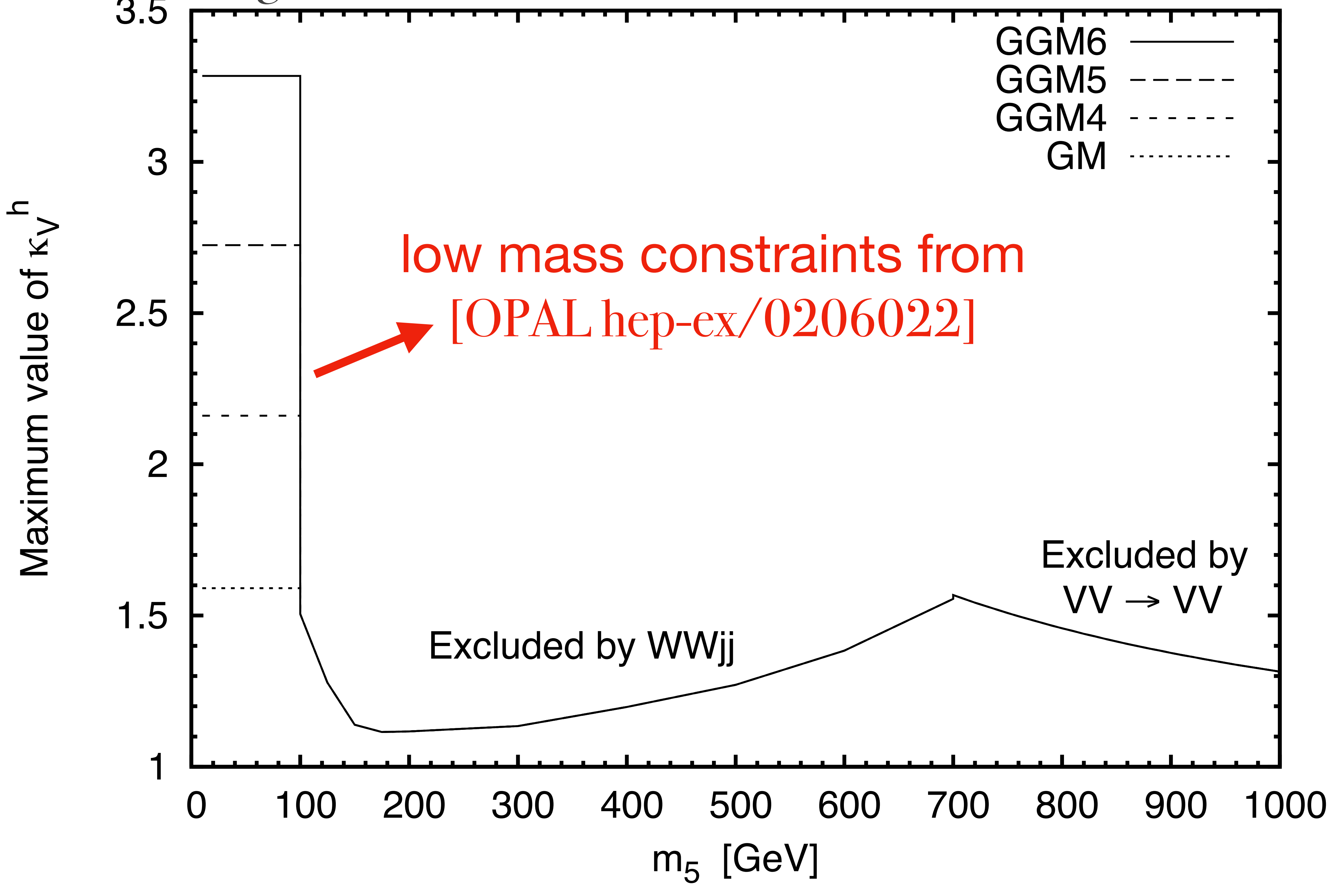
Thank you!

Backup

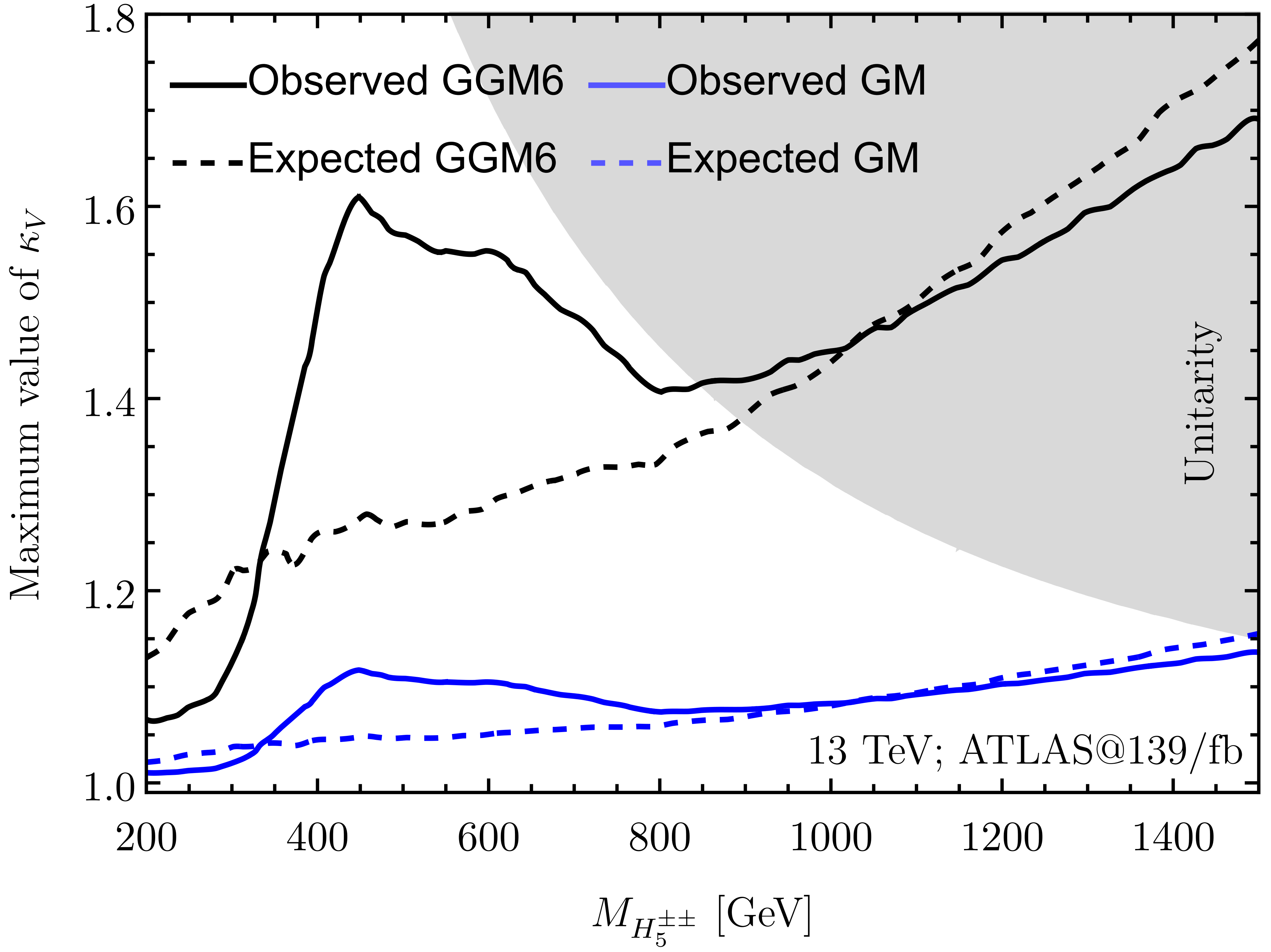
Enhancing κ_V

- Increasing κ_V quickly leads to issues with perturbative unitarity in many models
- Allowed in Georgi-Machacek models

[Logan, Rentala `15]

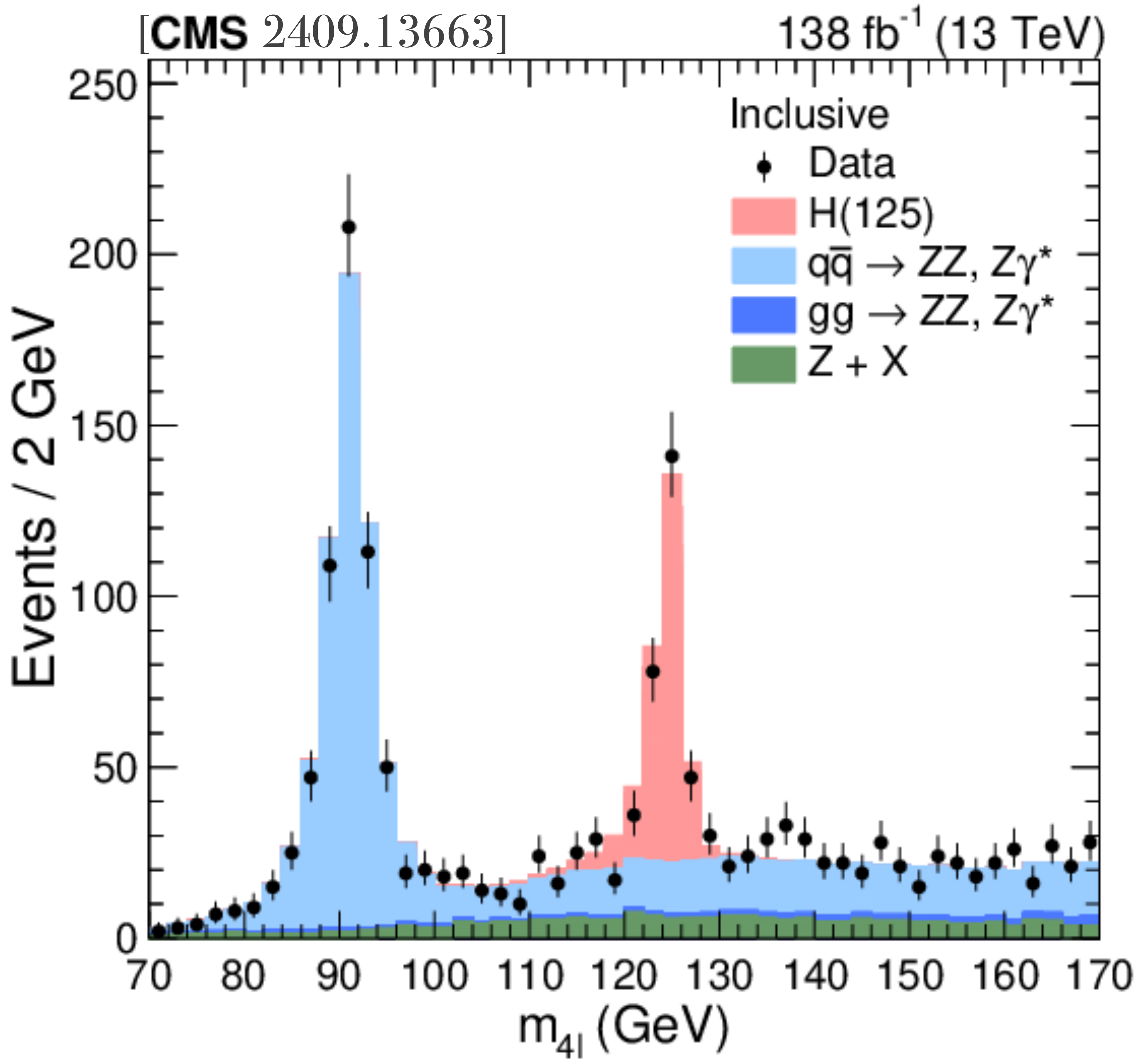


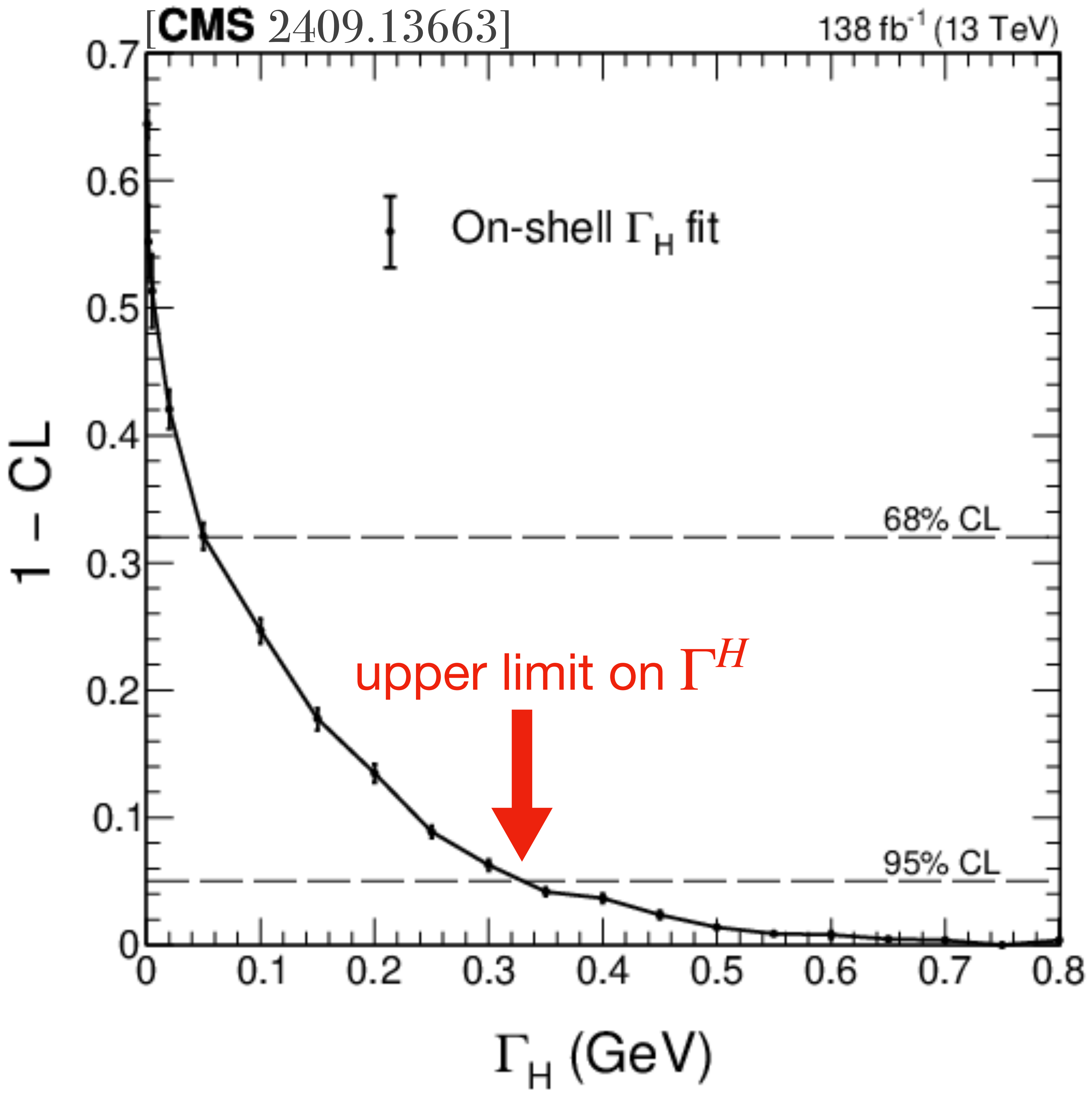
limits obtained using results of [ATLAS 2312.00420]
(VBF production of $H_5^{\pm\pm}$ with decays to WW)



Direct measurement of the Higgs width

- SM prediction for the Higgs width: $\Gamma^H = 4.1$ MeV [CERN Yellow Reports V2]
- CMS upper limit on Higgs width in the on-shell $gg \to H \to ZZ^*$ channel at $95\,\%$: $\Gamma^H < 330 \text{ MeV}$





Direct limits are orders of magnitude weaker than SM prediction

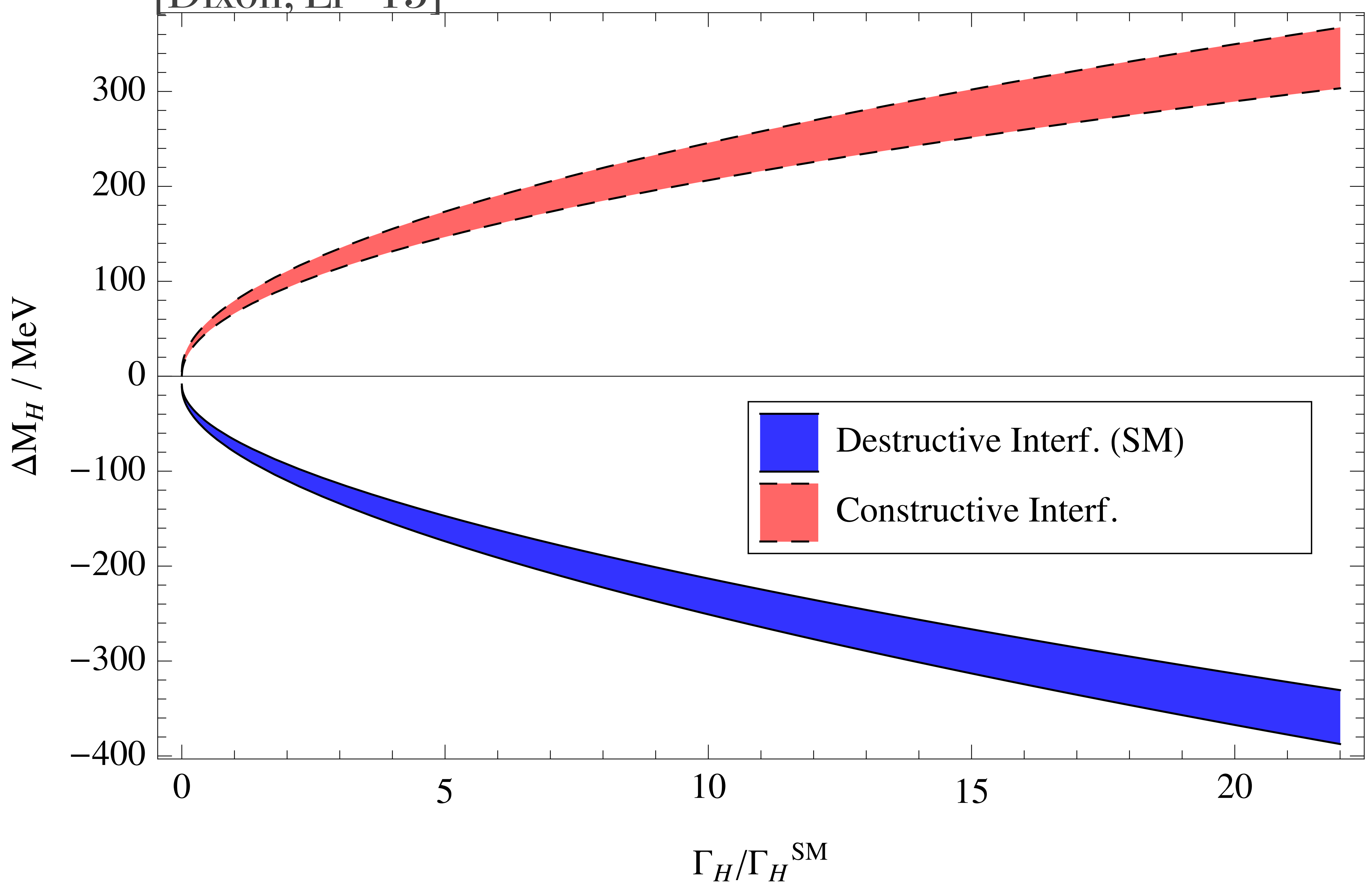
↓

Indirect measurements

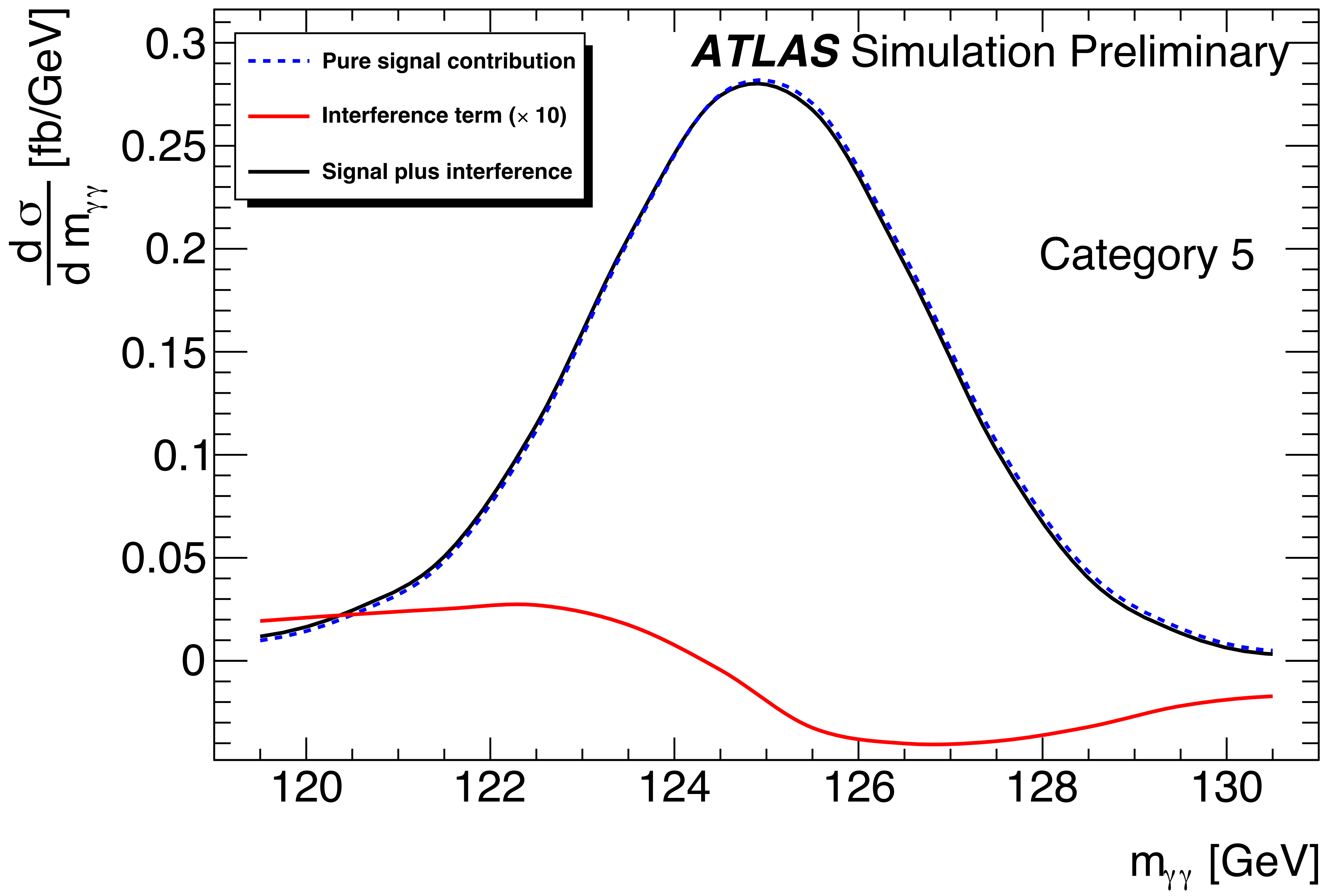
Indirect width measurement: mass shift

- Large interference between $gg \to H \to \gamma\gamma$ and background $gg \to \gamma\gamma$ creates a mass shift in $m_{\gamma\gamma}$
- Can compare the peaks in $\gamma\gamma$ and 4ℓ channels and use the shift to probe Γ_H [Dixon, Li ` 13]
- Method limited by current mass resolution

[Dixon, Li ` 13]



[ATL-PHYS-PUB-2016-009]

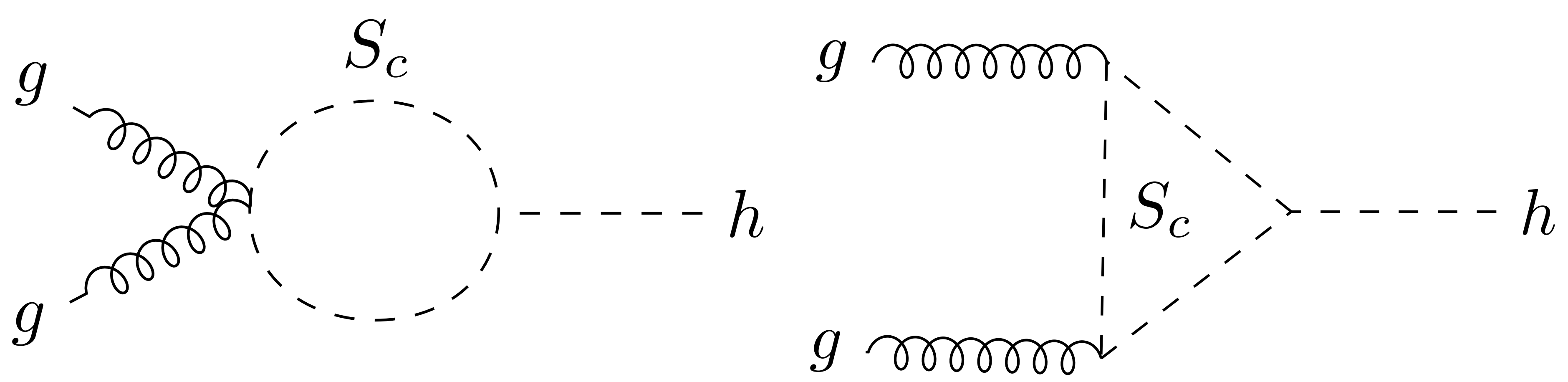


Gluon fusion modification: comparison

- Investigate simple extension with coloured scalar S_c:

$$\mathcal{L} \supset D_\mu S_c D^\mu \bar{S}_c - m_{S_c}^2 S_c \bar{S}_c + \lambda_{S_c} \Phi^\dagger \Phi S_c^\dagger S_c$$

leads to gluon-fusion modification



- Perturbativity is more complicated than before, we do not enforce a sum-rule

Simple analytical setup:

Modification of SM Higgs contribution:

$$\bar{\mathcal{M}} = \kappa_Z \left(\kappa_t + \frac{\lambda_{S_c} v^2 \left[1 + \tau_{S_c} f(\tau_{S_c})\right]}{m_H^2 \left[1 + (\tau_t - 1) f(\tau_t)\right]} \right)$$

for $\tau_i = 4 m_i^2 / p_H^2$

Loop function:

$$f(\tau_i) = \begin{cases} \arcsin^2 \tau_i^{-1/2} & \tau_i > 1 \\ -\frac{1}{4}\left[\log \frac{1+\sqrt{1-\tau_i}}{1-\sqrt{1-\tau_i}} - i\pi\right]^2 & \tau_i < 1 \end{cases}$$

Numerical setup:

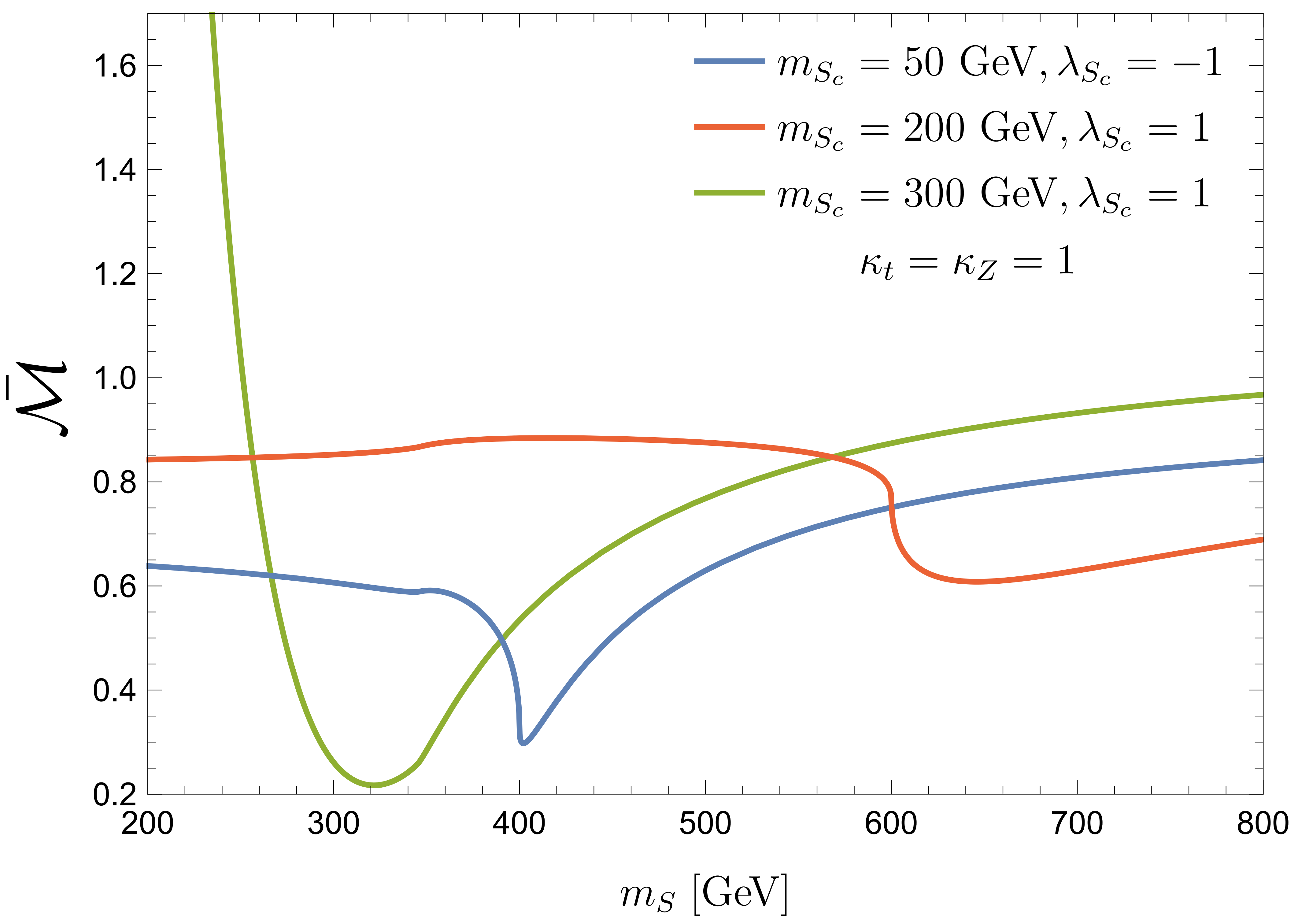
Parameterised cross section for $gg \to ZZ$:

$$d\sigma_{gg\to ZZ}(\kappa_t, \kappa_Z, \lambda_{S_c}) = d\sigma_{(0,0)} + \kappa_t \kappa_Z d\sigma_{(2,0)} + \kappa_t^2 \kappa_Z^2 d\sigma_{(4,0)} + \kappa_Z \lambda_{S_c} d\sigma_{(1,1)} + \kappa_t \kappa_Z^2 \lambda_{S_c} d\sigma_{(3,1)} + \kappa_Z^2 \lambda_{S_c}^2 d\sigma_{(2,2)}$$

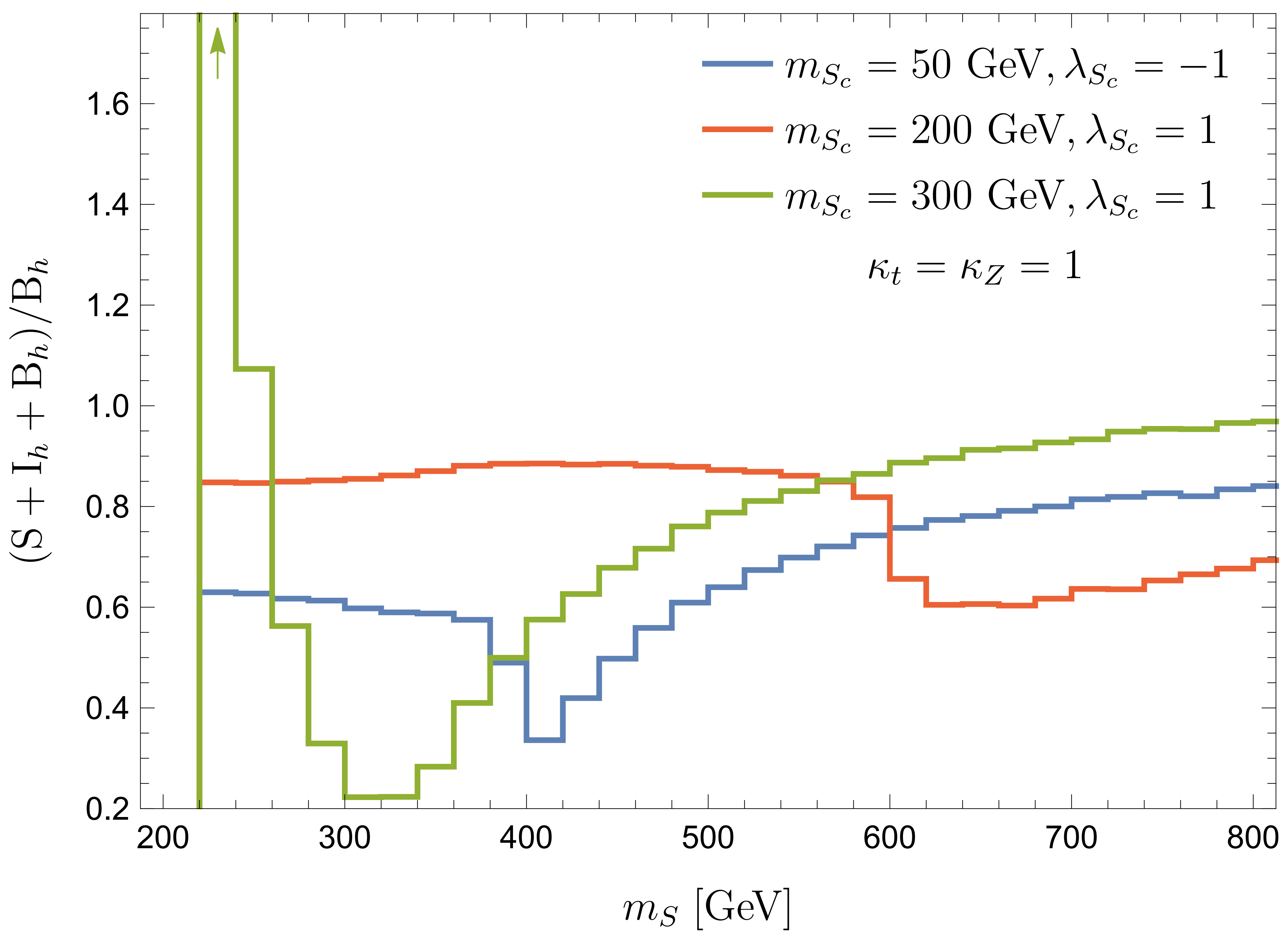
→ Can compare when box-contributions are not included (i.e. only $d\sigma_{(4,0)}$, $d\sigma_{(3,1)}$, $d\sigma_{(2,2)}$)

Coloured scalar: comparison with analytical

Simple analytical setup:



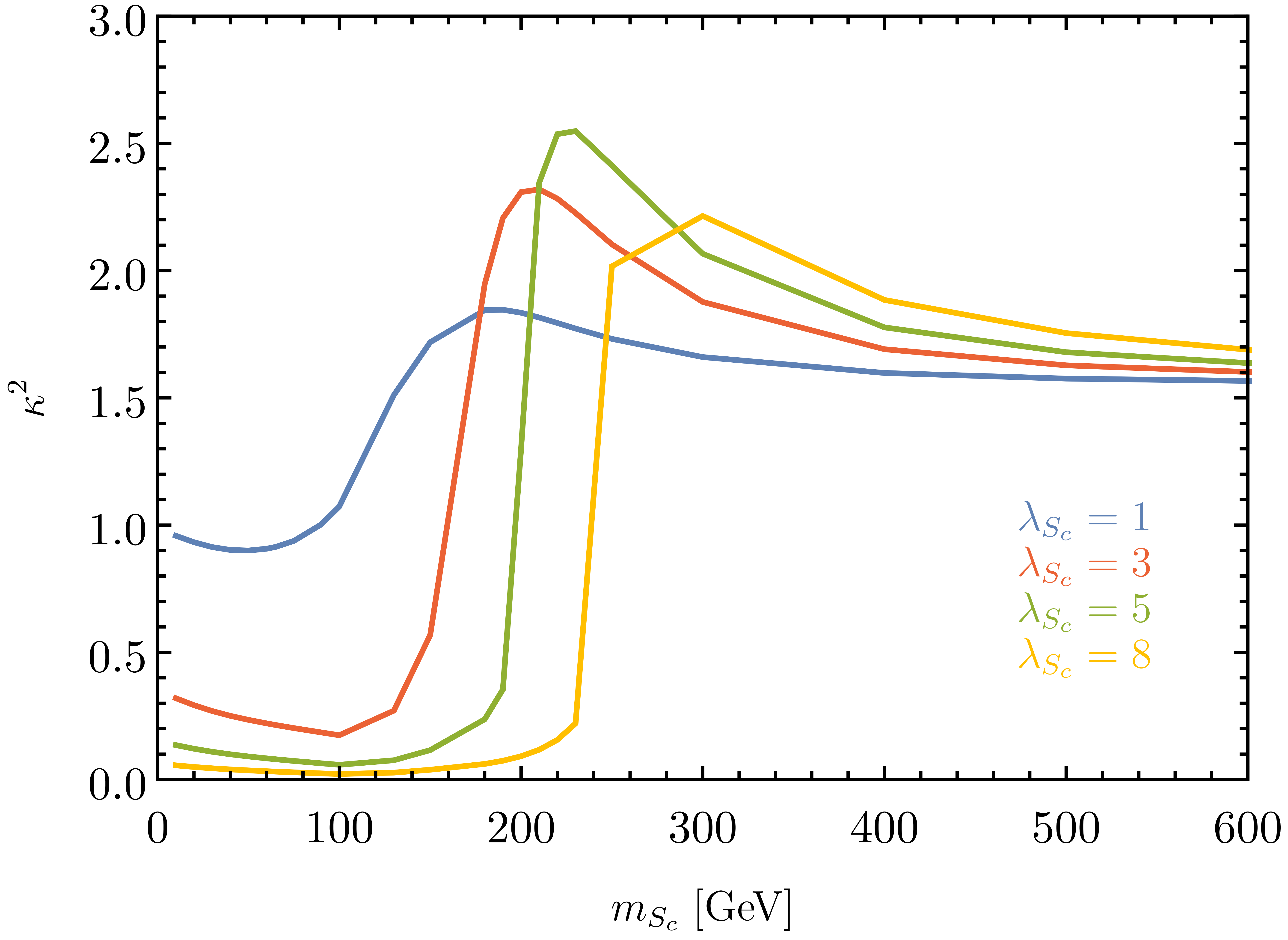
Numerical setup:



- **For small masses negative λ_{S_c} induces negative interference (and vice-versa for large masses)**

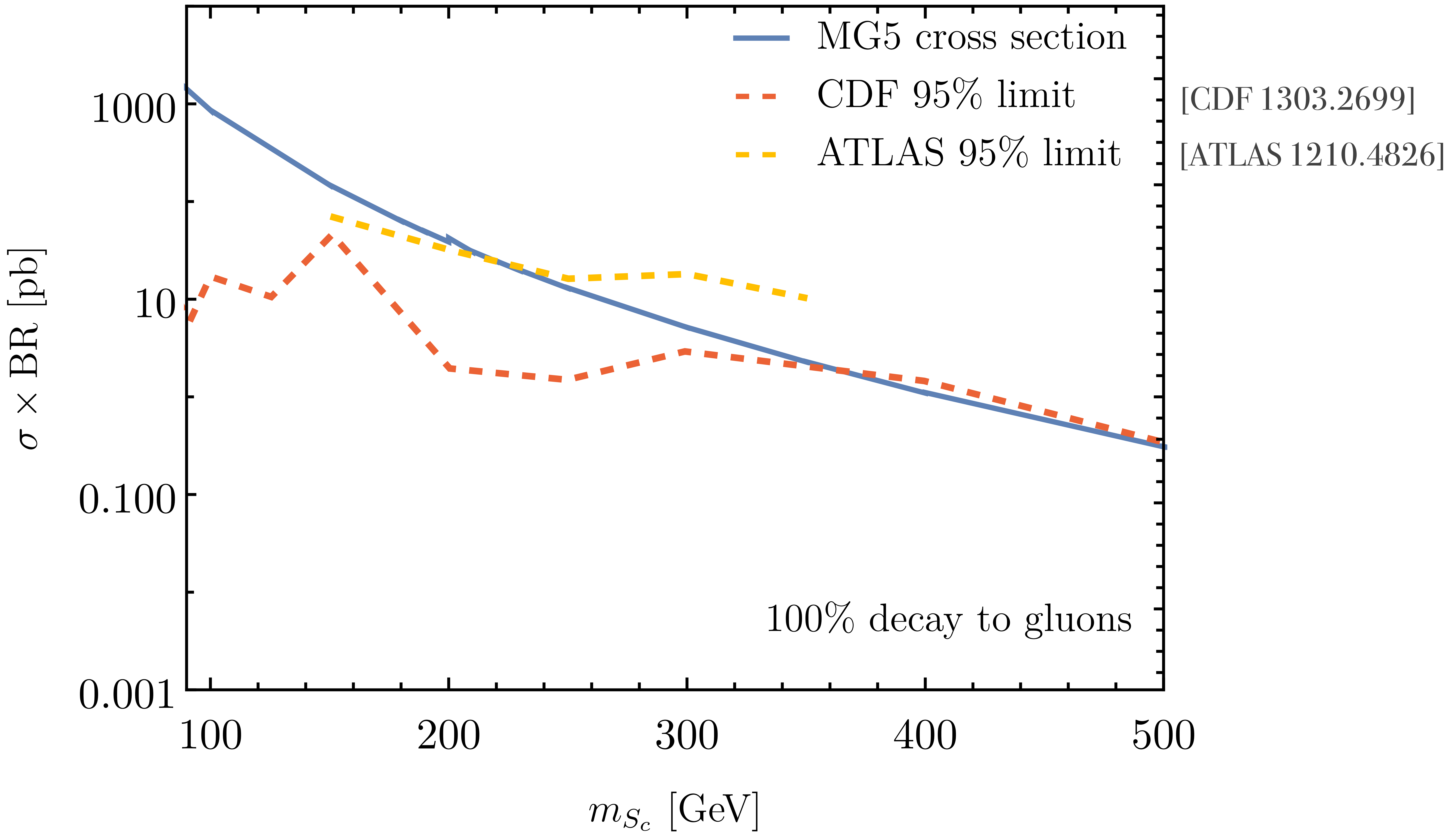
Coloured scalar κ^2 limits

- Increasing λ_{S_c} does not necessarily increase upper limit on κ^2



Coloured scalar: limits from cross section

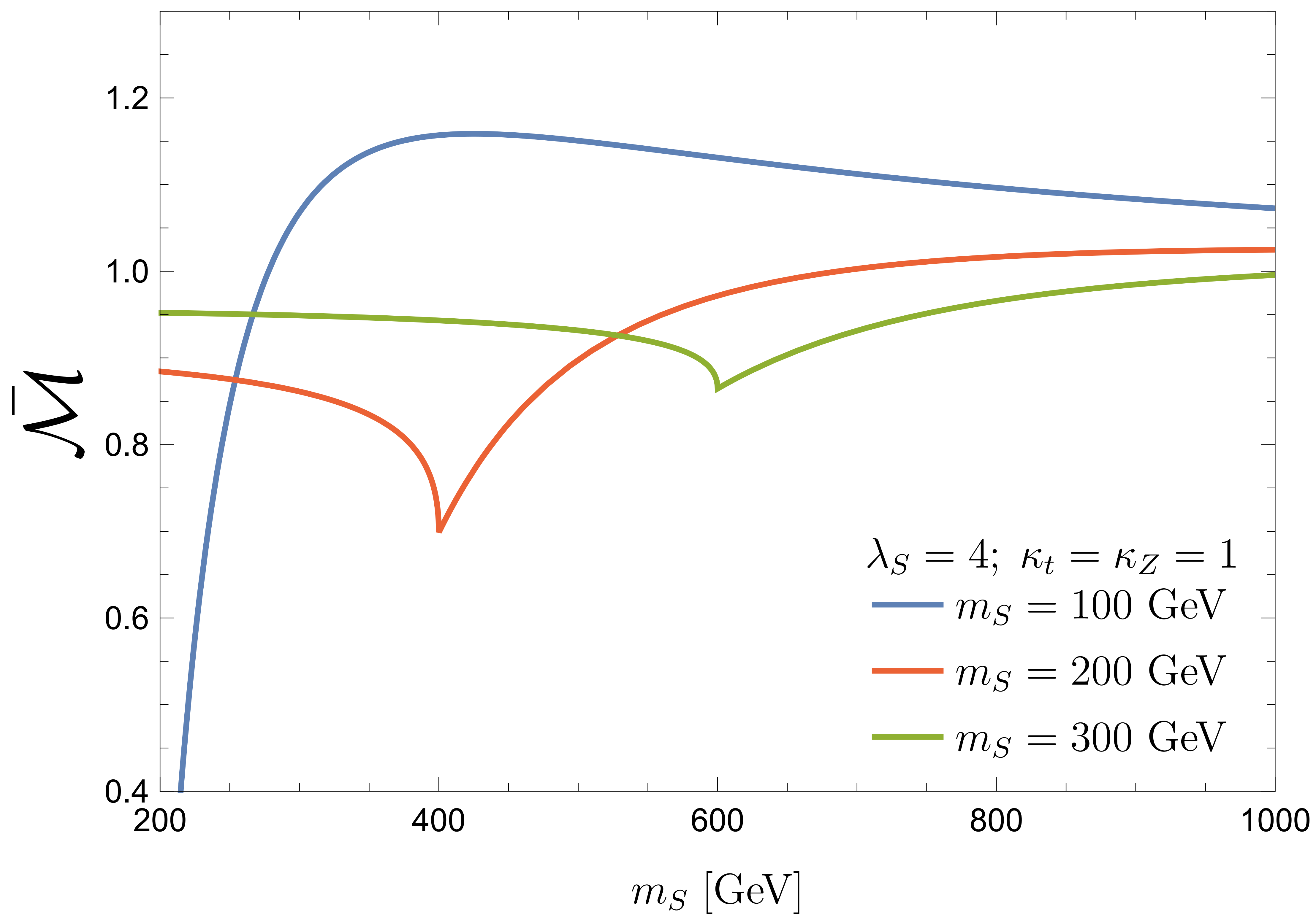
- Assuming that the coloured scalar is only coupled to gluons, the region $m_{S_c} < 230$ GeV would be excluded



Higgs portal: comparison with analytical

- Check implementation without any box contributions

Analytical setup:



Numerical setup: